Top-down and bottom-up decision-making for climate change adaptation. An application to flooding.

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Declaration

I declare that this thesis and the papers within it have been composed by myself and that no part of this thesis has been submitted for any other degree or qualification. The work described is my own unless otherwise stated.

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Abbreviations

AAD	Annual average damage
BN	Billion
CBA	Cost-Benefit Analysis
CEA	Cost-Effectiveness-Analysis
CMIP5	Coupled Model Intercomparison Project Phase 5
EC	European Commission
EU	European Union
GBM	Geometric Brown Motion
HA	Hectare
HEC-HMS	HEC Hydrologic Modelling System
IPCC	Intergovernmental Panel on Climate Change
MCA	Multi-Criteria Analysis
MCH	Multi-coloured handbook
NFM	Natural Flood Management
NGO	Non-gouvernmental organisation
NPV	Net present Value
NRO	Non real option
OA/GCMs	Ocean/atmosphere/general circulation models
PA	Portfolio Analysis
PMT	Protection Motivation Theory
RCP	Representative Concentration Pathways
RDM	Robust Decision-Making
ROA	Real Options Analysis
RP	Return period
UK	United Kingdom
UK NEA	United Kingdom National Ecosystem Assessment
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
WFD	Water Framework Directive
WMO	World Meteorological Organisation
WTP	Willingness-to-pay

Abstract

There is strong scientific consensus on the evidence of anthropogenic climate change which will increasingly present social, economic and institutional challenges. The Fifth Assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) established that 'human influence on the climate system is clear' and that 'changes in many extreme weather and climate events have been observed since about 1950' (IPCC 2014a). Associated impacts include sea level rise and increased likelihood of extreme weather worldwide such extreme rainfall, heat waves, hurricanes and tornados (IPCC 2014a; Klijn et al. 2015). Climate change adaptation is the adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects in order to minimise the impacts and to take advantage of new opportunities (IPCC 2007). Many vulnerable countries, regions and cities have accepted that some form of adaptation is inevitable (Swart et al. 2014).

This thesis contributes to the research on decision-making for climate change adaptation in order to reduce vulnerability. Both bottom-up and top-down analyses are applied to complement one another with an application to flooding. Flood risk is expected to increase in the UK under climate change (Alfieri et al. 2016; Scottish Government 2016) associated significant economic damage (CEA 2007).

From a top-down perspective, the thesis explores how to enhance economic decision-making under climate change uncertainty. In a situation of uncertainty the costs may be clear and immediate whereas the benefits are uncertain and often only realised in the distant future. This impedes the use of standard decision-making tools such as cost-benefit analysis that rely on the quantification of (expected) costs and benefits.

The thesis begins on the macro scale with a taxonomy of economic decision-making tools for climate change adaptation, discusses the sector level and subsequently proceeds to the case study micro-scale with applications of adaptation decision-making.

First, the potential of alternative decision-making tools, so-called robust decision-making approaches, is examined. The strengths and weaknesses of these tools relative to traditional decision-making processes such as CBA are explored and their future potential in the adaptation process evaluated. It is found that robust decision-making tools under

uncertainty provide performance across a range of climate change scenarios, but they may yield lower overall performance if compared with the alternative strategy under the actual climate outturn. Furthermore, they are resource intense and decision makers need to balance the resources required for employing the methods with the added value they can offer. A flow-chart is developed to provide guidance on which decision-making tool should be applied depending on the scale and type of adaptation project.

On the sector level, the economic appraisal of adaptation options for agriculture is explored. Agriculture is particularly vulnerable to climate change due to the direct impacts of weather and climate on agricultural output and the sector plays an indispensable role in providing (and improving) food security as well as creating employment. Many of the adaptation options in agriculture involve short-term managerial changes and can be appraised with standard economic decision-making and the options can be carried out after the climate signal has been observed. For those adaptations that do require a longer time to take effect or are long-lived and are (partly) irreversible in nature, robust approaches have a valuable role to play in decision-making. Suggestions are made regarding how robust decision-making tools under uncertainty can be practically applied to adaptations in agriculture, outlining the data needs and the steps of the data analysis for three different applications.

On the micro level, for a case study in the Eddleston Water catchment in the Scottish borders, UK, two different economic appraisal tools are applied. These include a cost-benefit analysis of afforestation as a flood management measure under different climate change scenarios which can provide important insights for adaptation decisions when robust decision-making tools under uncertainty are not feasible due to resource constraints. It is found that the flood risk under climate change increases substantially in the case study area which needs to be taken into consideration for economic appraisal. The results of the CBA reveal that all modelled scenarios of afforestation have positive NPVs which are driven by further eco-system services (including climate regulation, water quality and recreation) rather than flood regulation benefits. It is concluded that eco-system services beyond flood regulation should be considered for the appraisal of NFM to enable policy-makers to make informed decisions.

Second, the Expected values can be used in situations of quantifiable uncertainty, i.e risk. But for climate change we do not have a strong methodology to assess these subjective probabilities. They cannot be fully based on the past, because climate change is a new process for which we have no historical equivalent. Models share common flaws in their assumptions and their dispersion in results cannot be used to assess the real uncertainty (Hallegatte, 2012). The term deep uncertainty (Lempert et al., 2003) or severe uncertainty is used (Ben-Haim, 2006) in these contexts. Such uncertainty is characterised as a condition where decision makers do not know or cannot agree upon a model that adequately describes cause and effect or its key parameters (Walker et al., 2012). This leads to a situation where it is not possible to say with confidence whether one future state of the world is more plausible than another.

The robust decision-making tool under uncertainty real option analysis is applied to the same case study to allow for adjusting adaptation options over time by integrating lessons learned about climate change in the appraisal process. A simplified ROA is presented to minimise the life cycle cost of a system that aims to prevent flooding of a return period of 1/20 using tools which should be available to most public authorities. This includes the use of UKCP09 climate data, analysis of changes of peak flow under the measure implemented, cost structures for the measure and damage cost under different outcomes. The analysis can be carried out in an excel spread sheet with the aforementioned types of input. The results of the analysis demonstrate that the obtained strategy is significantly cheaper than planting for the worst case scenario and presents the potential for learning under climate change uncertainty as a way to allocate resources in a more efficient way.

The complementing bottom up approach investigates behavioural barriers to decision-making for adaptation. Standard economic theory tells us that self-interest will motivate most actors to engage in efficient private adaptation as long as the costs do not exceed the benefits. Thus, we would expect households at flood risk to invest in flood adaptation measures. However, it has been observed that households do not necessarily take action to protect themselves and their assets from flooding.

In a study carried out in co-operation with 36 communities around Scotland, protection motivation theory is used to explain the uptake of household flood protection and whether community led flood action groups can increase uptake. It is found that flood action groups directly and indirectly influence the uptake of some flood protection measures positively in particular if tailored information is provided.

Overall, it is concluded that both top-down and bottom-up approaches play an important role to move towards an economically efficient adaptation in the context of flooding. From a top-down perspective, uncertainty should be explicitly acknowledged and included in economic decision-making for adaptation (to flooding) to make an informed decision. The type of analysis will depend on the adaptation project and resources at hand. Developing and fostering bottom-up tools such as flood action groups to increase the uptake of the type of household flood protection with a benefit-cost ratio above 1 may also contribute towards the more efficient allocation of resources.

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1 Introduction

There is strong scientific consensus on the evidence of anthropogenic climate change which will increasingly present social, economic and institutional challenges. The Fifth Assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) established that 'human influence on the climate system is clear' and that 'changes in many extreme weather and climate events have been observed since about 1950' (IPCC 2014a). Event attribution studies have attempted to determine to what extent anthropogenic climate change has altered the probability of specific events (Herring et al. 2015; Herring et al. 2014; Kay et al. 2011; Pardeep et al. 2011; Peterson et al. 2012). Such studies have shown conclusive evidence for human impact having increased the probability of many particularly warm seasonal temperatures and reduced the probability of particularly cold seasonal temperatures in many places. The evidence for human influence on the probability of extreme precipitation events, droughts, and storms is more mixed but growing (Stott et al. 2016). The projections going forward – despite the unavoidable uncertainty - show further changes in temperature averages depending on different emission scenarios (IPCC 2014a). An increasing number of scientific studies suggest that global warming will exceed 2 °C and may even reach 6 °C by the end of the century (Betts et al. 2011; Friedlingstein et al. 2014). In addition, more frequent hot and fewer cold temperature extremes over most land areas on daily and seasonal timescales are considered virtually certain. Associated impacts include sea level rise and increased likelihood of extreme weather worldwide such extreme rainfall, heat waves, hurricanes and tornados (IPCC 2014a; Klijn et al. 2015).

Mitigation of and adaptation to climate change should be complementary strategies for reducing and managing the risks related to climate change. Mitigation refers to efforts to reduce or prevent emission of greenhouse gases (UNEP 2016). It is urgently needed and may also be the most efficient strategy as shown by Stern (2007), but its enforcement remains to be seen despite the concerted international policy efforts of the United Nations Framework Convention on Climate Change (UNFCCC). There is increasing acknowledgment that due to historic emissions and the inertia of the climate system even a large reduction of CO_2 would not prevent warming in the short-term (Klijn et al. 2015). Also, rapid reductions in anthropogenic carbon emissions appear increasingly unlikely (Le Quéré et al. 2015). Zeebe et al. (2016) showed by studying deep sea sediments, that humans are releasing carbon ten times faster than during any event in the past 66 million years, with 2014 being the record year of carbon release of about 37 billion metric tons of CO_2. A recent study on the melting of the Antarctica ice under climate change showed its collapse would raise sea levels by more than a metre by 2100 and more than 15 metres by 2500 if emissions continue unabated. These are changes that would profoundly change the surface of the earth. Hardly any impact on sea level rise due to Antarctic ice would be felt if emissions were quickly reduced to stay below the 2°Celsius limit (Deconto and Pollard 2016). The Paris Climate Agreement of December 2015 developed a longer-term strategy to keep temperature below the 2°Celsius limit with national ratifications on-going in June 2016, however the implementation remains to be seen given the voluntary nature of many of the elements of the pact (Evan and Yeo 2015). Also, Gasser et al. (2015) demonstrated that staying below 2°C may require capturing and storing carbon of an amount that exceeds the capabilities of current technology in all but the most optimistic case.

Given this evidence, many vulnerable countries, regions and cities have accepted that (some) adaptation is inevitable (Swart et al. 2014). Climate change adaptation is the adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects in order to minimise the impacts and to take advantage of new opportunities (IPCC 2007). Adaptation can be anticipatory, i.e. before the climate change signal has occurred or reactive, i.e. after the climate change signal has occurred; private and public; as well as autonomous and planned. Interrelated with adaptation are the concepts of adaptive capacity, vulnerability, resilience, exposure and sensitivity (see table 1-1 for definitions of all the terms taken from the IPCC glossary (Baede et al. 2014). The key aim of adaptation is to reduce vulnerability. 'Vulnerability of any system (at any scale) is reflective of (or a function of) the exposure and sensitivity of that system to hazardous conditions and the ability or capacity or resilience of the system to cope, adapt or recover from the effects of those conditions', Smit ((2006), p. 286).

Adaptation	Initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects. Various types of adaptation exist, e.g. anticipatory and reactive, private and public, and autonomous and planned.
Adaptive capacity	The whole of capabilities, resources and institutions of a country or region to implement effective adaptation measures.
Autonomous adaptation	Adaptation that does not constitute a conscious response to climatic stimuli but is triggered by ecological changes in natural systems and by market or welfare changes in human systems. Also referred to as spontaneous adaptation.
Exposure	The presence of people; livelihoods; environmental services and resources; infrastructure; or economic, social, or cultural assets in places that could be adversely affected
Planned adaptation	Adaptation that is the result of a deliberate policy decision, based on an awareness that conditions have changed or are about to change and that action is required to return to, maintain, or achieve a desired state.
Resilience	The ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organisation, and the capacity to adapt to stress and change.
Sensitivity	Sensitivity is the degree to which a system is affected, either adversely or beneficially, by climate variability or climate change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise).
Vulnerability	Vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.

Table 1-1 Definition of relevant terms based on the IPCC Glossary (Baede et al., 2014)

The scale of adaptation can be at the level of an individual or household, for instance to flooding as a climate stressor but also at the community, regional, national or even global level including the entire ecosystem. The scales will likely influence whether bottom-up or top-down strategies will be applied. Bottom-up approaches are concerned with how vulnerable individuals and/or communities are to climate variability and how their resilience can be improved through adaptation (Dessai and Hulme 2004). Top-down approaches are likely larger scale and generally start out with climate change projections that are combined with a decision-framework to develop anticipatory adaptation strategies (Dessai and Hulme 2004). Top-down approaches are often associated with a public decision-maker and planned adaptation whereas bottom-up approaches tend to focus more on autonomous private adaptation triggered by changes in the climate system. Both approaches have their place in adaptation and complement each other. Actions from both the public and private sector (firms, individuals, households) will be needed to manage the adaptation challenge. An important element to climate change adaptation is the uncertainty surrounding it. We only have partial knowledge of the future such as the rate and magnitude of change of climate and potentially non-linear changes which impedes adaptation in particular for long-time horizons (Dessai and Sluijs van de 2007).

Climate change will impact (almost) every sector and effective adaptation will present a complex challenge to society requiring different disciplinary input to adaptation decisions. This includes insights from social sciences such as psychology (e.g. how to overcome behavioural barriers to adaptation), political science (e.g. governance structures for adaptation), economics (e.g. efficient investment decision-making), natural science such as climate science and physics (e.g. to project the extent and approximate timing of impacts) to mention only a few disciplines.

This thesis uses insights from social and natural sciences generally and economics, psychology, sociology, climate science and hydrology specifically, to contribute to the research on decision-making for climate change adaptation in order to reduce vulnerability. Both bottom-up and top-down analyses are applied to complement each other.

The thesis aims to (1) enhance decision-making under uncertainty from a top-down perspective and (2) address behavioural barriers to decision-making from a bottom-up perspective.

Those two research aims were identified as important challenges within the climate change adaptation literature and relevant research objectives have been formulated to achieve those aims applied to flooding. A flood is an overflowing of a large amount of water beyond its normal confines, especially over what is normally dry land (Stevenson 2010). Flood risk is expected to increase in the UK under climate change (Alfieri et al. 2016; Scottish Government 2016) with associated significant economic damage (CEA 2007).

Section 1.1 explains the motivation for the research aims and identifies the objectives to reach those aims. Section 1.2 provides a brief overview of the structure and content of the research chapters and links them to the research objectives.

1.1 Decision-making for climate change adaptation

1.1.1 Decision-making under uncertainty

Section 1.1.1 describes three research issues identified as being relevant within the field of decision-making under uncertainty moving from the macro level to the sector and micro level in the context of climate change adaptation.

The macro level

Agreeing on the choice of an optimal investment is difficult for any complex project involving a number of stakeholders with different priorities but the uncertainty surrounding climate change makes such investment decisions considerably more challenging. Despite advances in modelling climate systems, substantial uncertainty persists and is unlikely to be resolved in the near future. Uncertainty stems from natural variability, modelling and downscaling, but also from the unknown extent of mitigation in the future, socio-economic changes which may increase or decrease the value of assets at risk and the preferences of future generations (Dessai and Sluijs van de 2007).

Climate change uncertainty is characterised as deep. Deep uncertainty is a 'situation in which analysts do not know or cannot agree on (1) models that relate key forces that shape the future, (2) probability distributions of key variables and parameters in these models, and/or (3) the value of alternative outcomes', (Hallegatte, 2012, p. 2).

Despite this deep uncertainty, decisions about implementing adaptation options still need to be made to effectively reduce vulnerability to climate change. In order to make the investments worthwhile, the costs cannot exceed the benefits. However in a situation of deep uncertainty, the costs may be clear and immediate, and the benefits uncertain and often being realised in the distant future. The stakes increase with projects that have long time-frames and cannot be easily reversed, such as infrastructure investments (Hallegatte et al. 2012). This results in challenges to economic appraisal through decision-making tools such as cost-benefit analysis which rely on quantifiable benefits at least with expected values which can be used to characterise risk. Expected values can be used in situations of quantifiable uncertainty, i.e risk. But for climate change we do not have a strong methodology to assess these subjective probabilities. They cannot be fully based on the past, because climate change is a new process for which we have no historical equivalent. Models share common flaws in their assumptions and their dispersion in results cannot be used to assess the real uncertainty (Hallegatte, 2012). The term deep uncertainty (Lempert et al., 2003) or severe uncertainty is used (Ben-Haim, 2006) in these contexts. Such uncertainty is characterised as a condition where decision makers do not know or cannot agree upon a model that adequately describes cause and effect or its key parameters (Walker et al., 2012). This leads to a situation where it is not possible to say with confidence whether one future state of the world is more plausible than another.

However, in the context of climate change, following from the definition of deep uncertainty, obtaining such expected values based on probability distributions may not be feasible. Thus, on the one hand, there is the need for action to reduce climate change vulnerability and advance adaptation but on the other hand, the deep uncertainty hampers the investment.

As a consequence, alternative approaches for decision-making, so-called robust decision-making tools under uncertainty are increasingly explored both in the academic and policy literature (Dessai and Hulme 2007; Dessai and Sluijs van de 2007; European Commission 2013a; Fankhauser et al. 1999; Hallegatte and Corfee-Morlot 2011; Hallegatte et al. 2012; Lempert and Schlesinger 2000; Ranger et al. 2010; UNFCCC 2009; Watkiss et al. 2014; Watkiss et al. 2009). The aim of these tools is to better incorporate uncertainty while still delivering adaptation goals, by selecting projects that meet their purpose across a variety of plausible futures (Hallegatte et al. 2012). The literature suggests the potential of such tools, however applications remain few which poses the question of how suited robust decision-making tools under uncertainty and standard economic decision-making tools are for different applications in the context of climate change adaptation.

The sector level

Decision-making tools provide added value when they are applied to provide practical guidance for adaptation investment. Such investment needs to occur in areas which are vulnerable to climate change. Vulnerability depends on a range of factors including amongst others geographic location and sector characteristics. Some sectors are more exposed than others. Agriculture, for example is particularly vulnerable to climate change due to the direct impacts of weather and climate on agricultural output (Iglesias et al. 2012). Increased average temperature, drought and flooding all impact crops and livestock. The agricultural sector plays an indispensable role in providing (and improving) food security as well as creating employment among 10 million people working full-time and 25 million people working part-time in agriculture in Europe (European Commission 2013b). Thus, given the economic importance of the livestock sector in Europe, minimising the impact of climatic changes on its output through effective and strategic implementation of adaptive practices will be critical. Many of the adaptation options in agriculture involve short-term managerial changes, such as adjustments to the timing of operations, the movement of stock in response to weather and climate variables. There are also some options regarding farm infrastructure or resilience to increased weather variability that involve longer time frames. However, there is relatively little guidance on economic appraisal in agriculture for climate change adaptation. Such guidance will depend on the type of the adaptation option, its life and lead time and associated with this its flexibility and reversibility. This guidance would ideally lead to the recommendation of a suitable appraisal tool depending on the differing characteristics of the adaptation options.

The micro level

Case studies are needed to illustrate and advance the application of decision-making tools for climate change adaptation for practitioners and policy makers. This includes both standard decision-making tools such as cost-benefit analysis as well as robust decision-making tools under uncertainty depending on the type of adaptation option and the resources available.

Flooding is one of the key risks of climate change and relevant to many economic sectors such as agriculture but also to households. Flooding is likely to occur more frequently under climate change (IPCC 2012). Flood risk management of different types and forms will therefore be an essential adaptation option. This not only includes 'hard' engineering measures but also 'soft' measures such as natural flood risk management (NFM). While both hard and soft approaches to flood risk management differ considerably, they both have in common the requirement of comprehensive economic appraisal and the need to consider uncertainty when they are discussed as climate change adaptation options. Relevant case studies of this type of economic appraisal are much needed to advance the process of decision-making for climate change adaptation but also to inform policy-makers on specific investment decisions.

1.1.2 Behavioural barriers to adaptation decision-making

Standard economics tells us that self-interest will motivate most actors to engage in efficient private adaptation as long as the costs do not exceed the benefits (Mendelsohn 2000). The adaptation will be constrained by budget considerations, and poorer households will implement inexpensive adaptations, while richer households are able in principle to consider more alternatives.

In the context of flooding, which is likely to increase in Europe under climate change (Alfieri et al. 2016), we would expect households at flood risk to invest in flood adaptation measures such as sandbags, flood gates, as well as insurance. These measures have been shown to be effective and have a benefit-cost ratio greater than 1 (Kreibich et al. 2015). However, it has been observed that households do not necessarily take action to protect themselves and their assets from flooding (Bichard and Kazmierczak 2012; Kunreuther 1996; Peek and Mileti 2002). Yet such household level adaptation is necessary as there will not be comprehensive flood risk infrastructure in place to prevent flooding of all magnitudes. Indeed, based on cost-benefit analyses such flood risk infrastructure will not be worthwhile implementing in many locations where the assets at risk are few. The challenge therefore is how to encourage households to implement flood management measures, or in other words, how to remove the behavioural barriers to adaptation that area neglected in the basic economic approach.

1.1.3 Research objectives

The challenges and research issues identified in sections 1.1.1 and 1.1.2 motivate research aims (1) and (2) respectively.

Research aim (1): enhance decision-making under uncertainty from a top-down perspective.

Research aim (2): address behavioural barriers to decision-making from a bottom-up perspective.

The following objectives have been specified to achieve the respective research aims:

Research objectives (1a – 1d) to address research aim (1):

1a. On the macro level: To conduct a comprehensive overview of available decision-making tools for climate change adaptation and an analysis of their suitability under uncertainty and for applied work.

1b. On the sector level: to identify climate change adaptation options for the European livestock sector and to provide a detailed exposition of suitable decision-making tools for the appraisal of the adaptation options based on the uncertainty associated with the decision problem.

1c. On the micro level: to apply the decision-making tool 'scenario-based cost-benefit analysis' to afforestation as a flood risk management measure under climate change uncertainty for a rural catchment in Scotland.

1d. On the micro level: to apply the robust decision-making tool under uncertainty 'real options analysis' to afforestation as a flood risk management measure under climate change uncertainty for a rural catchment in Scotland.

Research objective (2a) to address research aim (2)

2a. To conduct an analysis of behavioural patterns for adaptation decision-making for household flood management and the impact of flood action groups on the uptake of measures in rural communities in Scotland.

Section 1.2 provides an overview of the research chapters and links them to the specified research objectives.

1.2 Chapter overview and novel contribution of the dissertation to the scientific discourse

Chapters 2 to 5 of this thesis address the research objectives 1a to 1d. Chapter 2 starts at the macro scale with a taxonomy of decision-making tools for climate change adaptation and proceeds through the sector level to a micro-scale case study with applications of adaptation decision-making.

Chapter 2 of this thesis addresses the research objective 1a. The novel contribution of the chapter to the existing literature on decision-making tools for climate change adaptation consists of a decision-making framework to guide decision-makers to the most appropriate appraisal method for their situation. A flow-chart is developed to provide guidance on what decision-making tool may be applied depending on the scale and type of adaptation project.

We also indicate which has not been done in other taxonomies of decision-making tools which methods may prove most promising as adaptation planning becomes increasingly critical. This is done by exploring decision-making tools for climate change adaptation, in particular alternative decision-making tools, so-called robust decision-making approaches under uncertainty. It explores the strengths and weaknesses of these tools relative to traditional decision-making processes such as CBA and evaluates their future potential in the adaptation process.

The second part of Chapter 2 addresses research objective 2b and considers further the topic of robust adaptation tools under uncertainty by exploring their application to European agriculture. The sector is particularly vulnerable to climate change due to the direct impacts of weather and climate on agricultural output. This section of Chapter 2 explores the applicability of different economic appraisal methodologies for livestock adaptation options, given the uncertainty surrounding climate impacts. As a novel contribution, recognised adaptation options available to the livestock sector are taken, their potential costs and benefits are gathered with the help of expert knowledge and recommendations on which appraisal method is most appropriate is provided given the characteristics of the options. Importantly, the options are differentiated according to their lifetime, which influences the appropriate appraisal tools. For adaptation options with a short lifetime, traditional appraisal methods are suited, whereas robust appraisal tools under uncertainty come into play where irreversibility and long-times of projects apply. As far as known, such a summarised classification of appraisal method to adaptation option has not previously been carried out and we believe provides a useful summary of ways to approach adaptation appraisal in the livestock sector. Three detailed examples of how the robust methods under uncertainty could be applied are provided to illustrate their application in practice. The focus is on farm decision-making within European livestock but the principles can be applied to a range of production systems.

Moving from the sector level to a local case study, in Chapter 3 research objective 1c is addressed and a CBA for climate change adaptation is carried out using climate change scenarios. The CBA is applied to afforestation as a natural flood management measure[1] for fluvial flooding[2] in Scotland. The application in Chapter 3 highlights the potential of a traditional decision-making tool such as CBA combined with climate change scenarios – when the resources at hand are not sufficient to implement a robust decision-making appraisal under uncertainty. The climate change scenarios have been obtained using the UKCP09 climate change projections by the Met Office (Murphy et al. 2009). The work shows the benefits of different possible afforestation implementations under different climate change scenarios. While natural flood management (NFM) is widely discussed and embraced at the policy level due to it being less disruptive than hard engineering flood management measures and cheaper to implement (Iacob et al. 2014), conclusive evidence of afforestation as an effective and efficient NFM measure has yet to be provided. Therefore the chapter serves multiple purposes and contributes in the following way to the academic discourse. Most importantly, it provides information on an efficient level of adaptation investment for flood risk infrastructure in the case study area where costs do not exceed benefits under different climate change scenarios. It also extends the bio-physical research on afforestation as a NFM measure. Finally, it provides much-needed information on the costs and benefits of afforestation as a NFM, including further eco-system benefits beyond flood regulation such as recreation and climate regulation given the current limited evidence.

Chapter 4 addresses research objective 1d and applies a robust-decision-making tool, real options analysis (ROA) in the same case study area in the Scottish Borders. ROA handles uncertainty by allowing for learning about climate change over time. It is designed in such a way that strategies can be adjusted or reversed over time when additional information becomes available. Here it is applied to the case study of afforestation as a NFM with the aim of minimising the life cycle cost of a system which aims to prevent a flood of a magnitude of 1/20 over the assessment period. The magnitude of a 1/20 flood is expected to

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[1] Natural flood management involves techniques that aim to work with natural hydrological and morphological processes, features and characteristics to manage the sources and pathways of flood waters. These techniques include the restoration, enhancement and alteration of natural features and characteristics, but exclude traditional flood defence engineering that works against or disrupts these natural processes (Forbes, 2015).

[2] Any relatively high stream flow overtopping the natural or artificial banks in any reach of a stream.

increase with climate change (Murphy et al. 2009). Planting more forest will decrease the level of flood risk, but comes with additional cost. The developed strategy explicitly includes these trade-offs by allowing for learning about climate change and specifying investment decisions at different points in time. The novel contribution of this chapter is two-fold. We develop a flexible real 'on' options strategy for planting forest and thus explore the use of ROA for natural flood risk management measures such as afforestation which has not been done before. In addition, a simplified approach to ROA which requires only the use of an excel spreadsheet is provided to improve the accessibility of the tool to practitioners.

Chapters 2 to 4 which address research objectives 1a to 1d assume a public decision-maker and planned adaptation with a mostly top-down approach.

Chapter 5 acknowledges the importance of bottom-up (autonomous) adaptation as a way to effectively complement top-down work and tackles therefore research aim (2) addressing behavioural barriers on the household level with the focus remaining on flooding.

The research on adaptation to extreme weather events, specifically flooding, on the household level has applied insights from psychology. It has been shown that protection motivation theory (PMT) explains adaptation behaviour well, i.e. the uptake of measures. The theory considers in particular the risk an individual feels exposed to but also her perceived ability and confidence to undertake an adaptation measure as well as the belief in the effectiveness of the measure (Bubeck et al. 2013; Rogers 1983). While this has been confirmed in various studies (see Bubeck et al. (2012a) for an overview), there remains progress to be made on how to influence people's confidence, ability and belief in effectiveness to improve uptake. Chapter 6 examines this question by analysing the effect of flood action groups around Scotland on the uptake of flood adaptation measures at the household level. These autonomous groups were founded in 2012 in small communities across Scotland with the aim of finding local solutions to flood risk, and to provide information and training on a number of flood-related issues, including the use of flood adaptation measures. Appropriately designed flood action groups may be a cost-effective way of increasing the uptake of flood management measures, in particular in small communities where large engineering measures may not be financially viable. The analysis applies statistical analysis from a survey carried out among communities with flood action groups in Scotland (n=124). The novel contribution of this chapter lies therefore in the analysis of the role of flood action groups in the uptake of flood risk management measures which to the knowledge of the author of this thesis has not been carried out before. This advances the current research as it moves from understanding which factors play a role in uptake to identifying means of influencing those factors (such as through flood action groups).

Finally, Chapter 6 concludes with a summary of the gained evidence and its limitations, some policy implications gained from both the top-down approach focusing on (robust) decision-making tools applied to flooding, and the bottom-up approach of enabling households to develop their adaptive capacity against flooding. Finally, it suggests further research avenues based on the findings of this dissertation.

2 A survey of decision-making approaches for climate change adaptation: are robust methods under uncertainty the way forward?

Ruth Dittrich, Anita Wreford, Dominic Moran

Ruth Dittrich is the main author of chapter 2.1 - 2.7. She conducted the literature research, developed the flow chart and wrote the descriptions of the methods as well as their discussion. Anita Wreford and Dominic Moran provided comments on the drafts of chapter 2 with respect to writing and structure.

Chapter 2 (sections 2.1 – 2.7) is published as a peer-reviewed article in Ecological Economics:

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Ruth Dittrich is also main author of chapter 2.8 – 2.11. She wrote the description of the methods as well as the discussion and compiled the information on adaptation options.

Kairsty Topp, Vera Eory and Anita Wreford provided expert knowledge to build table 2-1 and contributed to writing the introduction.

Anita Wreford and Dominic Moran offered feedback on the drafts of the chapter (2.8-2.11) in terms of structure and content.

Chapter 2 (sections 2.8-2.11) is currently under second review with the peer reviewed journal Regional Environmental Change.

2.1 Abstract

Applying standard decision-making processes such as cost-benefit analysis in an area of high uncertainty such as climate change adaptation is challenging. While the costs of adaptation might be observable and immediate, the benefits are often uncertain. The limitations of traditional decision-making processes in the context of adaptation decisions

are recognised, and so-called robust approaches are increasingly explored in the literature. Robust approaches select projects that meet their purpose across a variety of futures by integrating a wide range of climate scenarios, and are thus particularly suited for deep uncertainty. We review real option analysis, portfolio analysis, robust-decision making and no/low regret options as well as reduced decision–making time horizons, describing the underlying concepts and highlighting a number of applications. We discuss the limitations of robust decision-making processes to identify which ones may prove most promising as adaptation planning becomes increasingly critical; namely those that provide a compromise between a meaningful analysis and simple implementation. We introduce a simple framework identifying which method is suited for which application. We conclude that the 'robust decision making' method offers the most potential in adaptation appraisal as it can be applied with various degrees of complexity and to a wide range of options. The second part of chapter focuses on the application of robust-decision making tools in the livestock sector. We find that for many adaptation options for livestock agriculture, standard (expected) cost-benefit analysis is an appropriate tool. For adaptation options requiring long lead-times or those with long lifetimes, techniques incorporating uncertainty ('robust' methods) are more suitable, including real options analysis, portfolio analysis and robust decision-making. From a comprehensive list of adaptation options in the livestock sector we identify the most appropriate appraisal technique for each option, and describe the application of the robust methods to heat stress, flood risk and water management, illustrating how the methods would be applied as well as potential limitations.

2.2 Introduction

Climate change adaptation research has progressed significantly in the last decade, illuminating many different aspects in the field, including identifying potential adaptation options (Iglesias et al. 2012), exploring impacts under different scenarios (Stern 2007) and identifying relevant governance challenges in policy decisions (Huntjens et al. 2012; Pahl-Wostl 2009). But relatively few adaptation actions have actually been implemented (Wise et al. 2013). At the same time, climate change projections highlight the likelihood that humankind will have to prepare for severe changes: the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2013) indicates warming trajectories of global temperature will likely exceed two degrees by 2100 and a World Bank report (Worldbank 2012) projects that the planet is on track for a four degree Celsius warmer world by 2100. These reports go beyond the conceptualisation of climate change adaptation, making an emphatic call for adaptation actions in the present. Adaptation in many sectors will be reactive as the time frame for many decisions is too short to take into consideration the long-term climate signal. Adjusting growing seasons in agriculture according to changes in climatic conditions is a classic example. A farmer can implement such changes on a yearly or seasonal basis observing the prevailing weather. But implementing such incremental adaptations may not be sufficient in the long term, when anticipatory and planned adaptation is required; for example large infrastructure projects with long life times such as urban drainage structures, dams or sea walls. In some cases, society will want to avoid threshold events, such as the extinction of certain species. Moreover, extreme events may become more frequent and intense with climate change (IPCC 2012), which may also necessitate intervention now. Where anticipatory adaptation leads to a situation in which the system is over- or under-adapted to the future climate outcome, additional costs are incurred either through large residual climate change impacts, the waste of investment if changes are not as severe as projected, or through the failure to seize new opportunities arising from climate change. Fankhauser (2010) reviewed different studies of adaptation costs whose estimates range from around $25 billion a year to well over $100 billion for the next 20 years based on ‘median’ climate change. Considering that the impacts of climate change might only become more severe in the more distant future, these costs may be an underestimation, but also show the inherent uncertainty of the costs of adaptation. In the context of a global economic crisis that is only slowly receding, *a fortiori* the allocation of significant resources to adaptation needs to be carefully scrutinised to invest wisely in appropriate options. Economists strive to give investment recommendations that minimise costs and maximise benefits. In other words, to allocate resources optimally by finding the strategy that is better than any other alternative for a given situation. Decision-makers largely still use traditional economic analysis techniques for appraising adaptation investments, predominantly cost benefit analysis (CBA), which struggles to account for uncertainty. Methods that extend these tools are increasingly being discussed but applications remain relatively scarce. This chapter is the starting point of this dissertation with a taxonomy on decision-making tools for climate change adaptation that provides an comprehensive overview of tools to appraise adaptation options. In addition, we progress the existing literature on these techniques by providing a decision-making framework to guide decision-makers to the most appropriate appraisal method for their situation. We also indicate which methods may prove most promising as adaptation planning becomes increasingly critical.

We first summarise traditional decision-making approaches to appraise investment, describing briefly cost-benefit analysis, cost-effectiveness analysis and multi-criteria analysis, followed by the difficulties of applying these methods in the context of climate uncertainty. Section 2.4 then presents the conceptual basis of decision-making approaches that deal better with uncertainty, so-called robust methods under uncertainty. The overview is not exhaustive: it describes the methods and tools that are currently most discussed in the adaptation literature and in other taxonomies of decision-support approaches (Hallegatte et al. 2012; Herman et al. 2015; Jones et al. 2014; Kunreuther et al. 2014). We focus in particular on the underlying assumptions of these methods and on the conditions under which the methods work well, and illustrate each method with a number of applications from the literature. Subsequently, we provide in section 2.5 a simple framework summarising which adaptation problem is best appraised by which decision-making process. In section 2.6, we extend the discussion on robust methods under uncertainty by describing the limitations of robust decision-making methods under uncertainty, reflecting on why they have so far not been more widely applied in real projects. Finally, we outline the potential future direction of research for robust methods under uncertainty, identifying which may prove most promising for policy making; namely those that find a compromise between a meaningful analysis and simple implementation.

2.3 Traditional decision-making approaches

Cost-benefit analysis, cost-effectiveness-analysis and multi-criteria analysis are widely used decision-making approaches in policy analysis when appraising projects.

Cost-benefit analysis (CBA) attempts to maximise the benefits for society based on potential Pareto efficiency[3]. It assesses whether it is worthwhile to implement a project by comparing *all* its monetised costs and benefits expressed over a defined time span to obtain its net present value (NPV) as in equation 1:

$$NPV(i,N) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t} \qquad (1)$$

where N is the total number of periods, i the discount rate, t is time and R_t is the net benefits (benefits minus cost) at time t. For CBA in adaptation, climate change impacts and their value must first be estimated. For this, climate projections from coupled ocean/atmosphere general circulation models (OA/GCMs) under a range of greenhouse gas emission scenarios are downscaled. This output is then fed into impact models to determine for example changes in rainfall of or crop yields. Subsequently, the impact following the adaptation option must then also be valued, and the difference between pre- and post-adaptation impacts provides the net benefits of adaptation R_t. Additionally, the costs of adaptation must be estimated over this time period. Figure 2-1 illustrates how adaptation benefits are obtained.

[3] An allocation is Pareto efficient if no alternative allocation can make at least one person better off without making anyone else worse off.

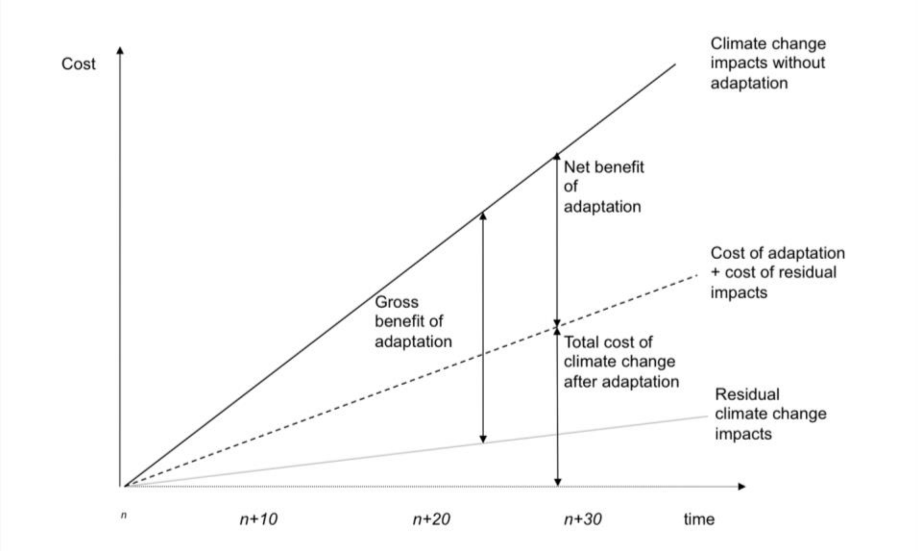

Figure 2-1 Costs and benefits of adaptation

The stream of benefits and costs over time are discounted to present values, and a net present value (NPV) is calculated by subtracting the net costs (cost of adaptation measure) from the net benefits (pre-adaptation minus post-adaptation impacts, thus avoided damages). A positive NPV indicates the project should generally proceed (Boardman et al. 2014). Alternatively, if the ratio of benefits to costs (“benefit-cost ratio’’) is larger than one, the investment is economically desirable. Providing reliable data on costs and benefits are available, CBA can be carried out with limited technical resources and the results are accessible to a non-technical audience (for applications, see for example (Escobar 2011) and (Willenbockel 2011).

Cost-effectiveness analysis (CEA) represents an alternative to cost-benefit analysis when it is difficult or controversial to monetise benefits, such as the value of lives saved or landscape values. CEA compares mutually exclusive alternatives in terms of the ratios of their costs and a single quantified, non-monetised effectiveness measure with the aim to choose the least cost option. CEA is relatively straightforward in terms of optimisation: when effectiveness across all options is assumed to be identical it amounts to a simple cost minimisation problem such as achieving an acceptable level of flood protection. When the budget is fixed, an effectiveness maximisation problem is solved. For applications to adaptation, see for example (Boyd et al. 2006) and (Luz et al. 2011).

CEA works best if the benefits of the adaptation options are identical given one metric. This might apply with regard to clearly defined technical solutions. But if neither costs nor benefits are identical, scale effects need to be considered: policies with low impact at a relatively low cost per unit will be ranked higher than policies that have high impacts at a somewhat higher cost (Boardman et al. 2014), (see also Kunreuther et al. (2014) for further comparison of CBA and CEA in the context of climate policy).

Multi-Criteria analysis (MCA) in its simplest application (whose complexity can be increased in various ways) usually consists of a combination of quantitative and qualitative (monetised and non-monetised) indicators that provides a ranking of alternatives based on the weight the decision-maker gives to the different indicators (see for example Garcia de Jalon et al. (2013) for an application). For example, distributional or psychological impacts for which it is difficult to assign a monetary value can be integrated according to the preferences of the decision-maker. Results from other methods such as cost-benefit analysis can be included (UNFCCC 2009). Through the weighting, the data is mapped onto an ordinal scale and both quantitative and qualitative data can be compared relatively, but not with regard to an absolute scale, prohibiting a generalisation of the results.

CBA, CEA analysis and MCA have all long been tested, further developed and successfully applied to many projects and policies, but policy makers face considerable challenges when applying these decision-making approaches in an area of uncertainty such as climate change adaptation. While the costs might be observable and immediate, the benefits of adaptation are harder to define, as these require planning and foresight about how the climate will change. Indeed, there is considerable uncertainty attached to climate change projections, as well as to the expected impacts and responses to them (Dessai and Sluijs van de 2007). In particular, uncertainty exists with regard to downscaled climate data such as localised data on precipitation, temperature and flood probabilities, which might not be resolved for a long time, if at all (Fankhauser and Soare 2013). Uncertainty also stems from the future emissions of GHG, how global and local climate systems will react to these changes in emissions as well as the response of other systems to climate change, including ecosystems (Wilby and Dessai 2010). Finally, there is uncertainty regarding knock-on effects on society and the economy depending on their vulnerability and adaptive capacity (Kunreuther et al. 2012) .

These unknowns make the application of the decision-making approaches described above at least in their 'basic' formulation challenging. The uncertainty can be addressed in different ways. For example, an expected values framework attaches "subjective probabilities" (Hallegatte et al. 2012), to evaluate the expected benefits as the probability-weighted average of the benefits based on how likely different states of the world are (Gilboa 2009). Probabilities can be based on past occurrences of events, expert knowledge, or both. Subsequently projects matching the conditions of that future are designed and fine-tuned with sensitivity analysis. Similar to this is expected utility—if the risk preferences of those affected are known (Watkiss et al. 2014). This approach is variously labelled as 'science first' (Ranger et al. 2010), 'top-down approach' (Wilby and Dessai 2010) or 'agree-on-assumptions' (Kalra et al. 2014) in the context of adaptation. Additionally, scenarios of how the future might unfold (of equal likelihood) can be used (Boyd et al. 2006; Garcia de Jalon et al. 2013); for CBA this is a variant to include more than the central estimate as in the expected value framework. Worst- and best cases that might be of particular interest in the context of climate change can be easily turned into scenarios. Related to this is the min/max approach that aims to minimize the possible loss for a worst case (maximum loss) scenario for prudency. Put differently, we choose the alternative such that its lowest possible expected value (i.e., lowest according to any possible probability distribution) is as high as possible (maximize the minimal expected value) (Von Neumann 1967). Reliability-weighted expected value calculates the weighted average of probabilities, giving to each probability the weight assigned by its degree of reliability (Howard 1988). Further variations of decisions under uncertainty exist (see Hansson (2005) for an overview) which all rely on attaching subjective probabilities to different outcomes.

All of these strategies have associated difficulties. Using several climate change scenarios provides the end-user with a range of possible outcomes, but with no attached probabilities making it difficult to make an informed decision (New and Hulme 2010). Expected values can be used in situations of quantifiable uncertainty. But for climate change we do not have a strong methodology to assess these subjective probabilities. They cannot be fully based on the past, because climate change is a new process for which we have no historical equivalent. Models share common flaws in their assumptions and their dispersion in results cannot be used to assess the real uncertainty (Hallegatte, 2012). The term deep uncertainty (Lempert et al. 2003) or severe uncertainty is used (Ben-Haim 2006) in these contexts. Such uncertainty is characterised as a condition where decision makers do not know or cannot agree upon a model that adequately describes cause and effect or its key parameters (Walker et al. 2012). This leads to a situation where it is not possible to say with confidence whether one future state of the world is more plausible than another. Also, challenges can arise if there is disagreement on the ethical judgment and worldviews as objectives need to be agreed upon (based on a decision criterion) (Hallegatte et al. 2012)

The limitations of traditional decision-making approaches for investment appraisal in the context of climate change have been recognised by many decision makers and governments. Alternative decision making approaches to appraise and select adaptation options are therefore being explored, both in the academic and policy literature (Dessai and Hulme 2007; Dessai and Sluijs van de 2007; European Commission 2013a; Fankhauser et al. 1999; Hallegatte and Corfee-Morlot 2011; Hallegatte et al. 2012; Lempert and Schlesinger 2000; Ranger et al. 2010; UNFCCC 2009; Watkiss et al. 2014; Watkiss et al. 2009). The aim is to better incorporate uncertainty while still delivering adaptation goals, by selecting projects that meet their purpose across a variety of plausible futures (Hallegatte et al. 2012); so-called robust decision-making approaches under uncertaintyes. These are designed to be less sensitive to uncertainty about the future and are thus particularly suited for deep uncertainty (Lempert and Schlesinger 2000). Instead of optimising for one specific scenario, optimisation is obtained across scenarios: robust approaches do not assume a single climate change forecast, but integrate a wide range of climate scenarios through different mechanisms to capture as much of the uncertainty on future climates as possible. This is achieved in different ways: by finding the least vulnerable strategy across scenarios (Robust Decision Making), defining flexible, adjustable strategies (Real Option Analysis) or by diversifying adaptation options to reduce overall risk (Portfolio Analysis). Furthermore, no or low regret options that perform well independent of the climate driver are also discussed in the context of robust methods under uncertainty, although they are not decision-making approaches *per se* but options.

For risk-averse decision-makers, robust strategies are attractive as they help to reduce the range of uncertainty in an investment decision. They can thus help to reach consensus on actions as different future scenarios and thus diverging viewpoints are better integrated, while reducing the risk of over- and under-adaptation. But different adaptation problems will require different techniques depending on the characteristics of the adaptation options and the nature of the uncertainty. While much discussed in the academic literature (Dessai and Hulme 2007; Fankhauser et al. 1999; Hallegatte and Corfee-Morlot 2011; Hallegatte et al. 2012; Lempert and Schlesinger 2000; Ranger et al. 2010; Watkiss et al. 2014; Watkiss et al. 2009) and in policy documents (European Commission 2013a; Frontier Economics 2013; UNFCCC 2009) so far relatively few applications exist.

2.4 Robust Decision-Making Approaches under uncertainty

2.4.1 Portfolio analysis

Portfolio Analysis (PA) is akin to combining shares in a portfolio to reduce risk by diversification (Markowitz 1952). Analogously, a basket of adaptation options is determined by maximising adaptation returns given the decision maker's risk affinity. Alternatively, given a defined return of the adaptation options, risk is minimised across all adaptation options for different climate change scenarios. A portfolio is best balanced if the co-variance of the assets is negatively related, off-setting the risk under different scenarios. In other words, a low return on one asset will be partly offset by higher returns from other assets during the same period. For example, solving for minimising risk for different target returns will provide a range of feasible portfolios specifying the weights (quantity) of the different adaptation options in each portfolio. The benefits can be expressed both in monetary and non-monetary terms, for instance as conservation values of wetland habitats (Ando and Mallory 2012), or as the potential to regenerate forests with different tree seeds (Crowe and Parker 2008). Figure 2-2 shows different feasible portfolios for different target returns on an efficient frontier. In the application of Ando and Mallory (2012), the benefit axis refers to the average expected value of conservation of land while the risk axis expresses the standard deviation of the conservation values. Thus the decision maker can make an explicit choice between average expected value of return and riskiness (standard deviation of the return); the higher risk, the higher the expected value.

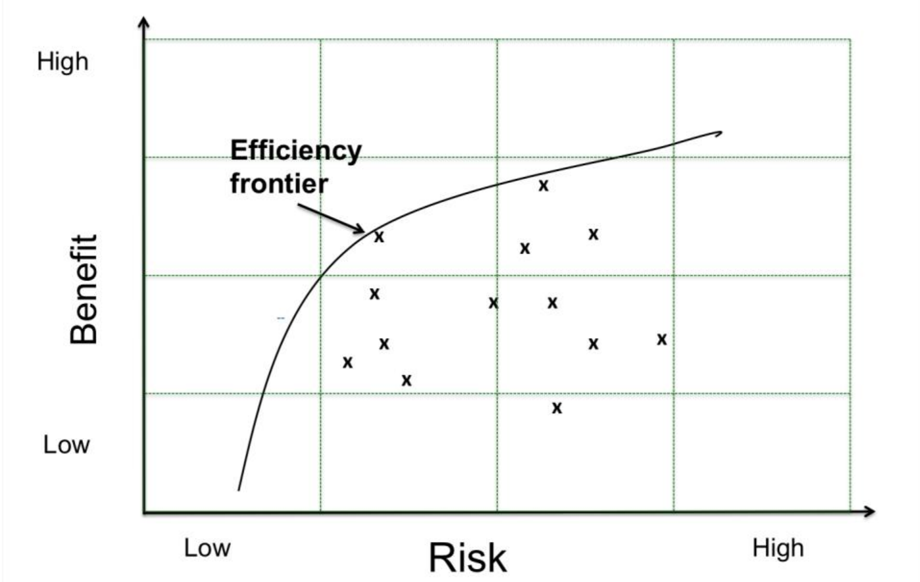

Figure 2-2 Efficiency frontier: a portfolio on the frontier is chosen according to risk preference.

PA thus allows a trade-off between the return and the uncertainty of the return of different combinations of adaptation options under alternative climate change projections. However PA still requires assumptions about probabilities of plausible climate change scenarios and associated impacts, and is thus still a 'predict-then act' decision-making process. The method also only works if the returns of the adaptation options are negatively correlated and their correlation can be well specified for a long term planning horizon. This might for example be a basket of locations where certain animal or plant species may be preserved.

The strict application criteria may account for the limited number of applications, which to date are focused in the area of conservation (Ando and Mallory 2012; Crowe and Parker 2008). But the technical requirements are not necessarily complex and returns may include both economic efficiency and physical effectiveness, so it would be worth exploring further applications. In the area of conservation management in particular, costs will often be quantifiable but benefits are likely to be much more difficult and controversial to measure. This is for example the case for ecosystem services of peatlands or forests where so far hardly any estimates exist (Moran et al. 2013) and might therefore be well suited for an application of portfolio analysis.

2.4.2 Real option analysis

Flexible and reversible approaches handle deep uncertainty by allowing for learning about climate change over time, and are designed in a way that they can be adjusted or reversed over time when additional information becomes available. Real Options Analysis (ROA) is one of several ways to formalize policies that adapt over time in response to new information.

Real Option Analysis (ROA) originates from financial economics (Black and Scholes 1972; Cox et al. 2002; Dixit and Pindyck 1994; Merton 1973) and extends the principles of cost-benefit analysis to allow for learning based on an uncertain underlying parameter.

The uncertain parameter in the context of climate change is a specific climate variable: rainfall, temperature or sea level rise, for example. ROA analyses whether it is worth waiting for more information, i.e. it estimates the value of additional information given the uncertainty surrounding climate change, instead of possibly over- or underinvesting now. Thus, there is a trade-off between obtaining the potential pay-off in the present and waiting for further scientific information in the future (Gollier and Treich 2003).

ROA relies on the assumption that uncertainty is dynamic rather than deep. Uncertainty is assumed to resolve to a degree with the passage of time due to increasing knowledge on climate change impacts. The idea can be illustrated in a simple decision tree as in figure 2-3.

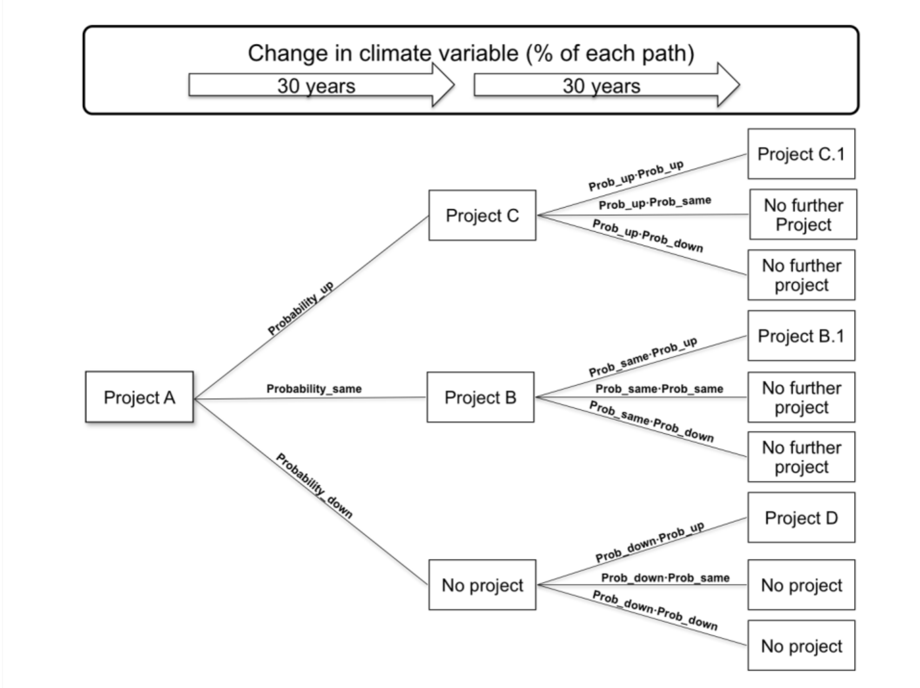

Figure 2-3 Real Option Decision Tree

Gersonius et al. (2013) applied this strategy to urban drainage infrastructure in West Garforth, England: the connecting lines in the decision tree in figure 2-3 depict the change in the climate variable rainfall intensity either upwards, downwards or remaining the same over a period of 60 years (divided into 30 year intervals). The decision nodes reflect adaptation options such as replacing sewer conduits or building and upsizing storage facilities. Given these climate paths, ROA looks at each and every possible scenario and indicates what to do in any of these contingent events, i.e. which adaptation option to implement. Thus, the strategy is adjustable and a specific implementation is chosen by observing the actual change of rainfall intensity over time. The aim may for example be to minimise the lifetime cost or maximise the lifetime benefit of the specific project. Project A is the initial adaptation option and investment C should be implemented after a period of 30 years, if the climate variable turns out to follow the upward path. Subsequently a set of further projects can be implemented approaching the end of the second period. The optimal choice made during the second period is determined by the choice made in the first period. Thus, an adaptation strategy is developed that can be adjusted if needed when reassessing the strategy in 30 years and again in 60 years as different plausible scenarios will have been considered today.

ROA works particularly well for partly reversible investments with long life times and sensitivity to climate conditions, when there is a significant chance of over- or underinvesting combined with an opportunity cost to waiting, i.e. if there is a need for action in the present. It has a timeliness and a flexibility implication: first, ROA evaluates the benefits of postponing part or all of an (irreversible) investment, and second, it can assess technical options created or destroyed through the project (Wang and De Neufville 2005). Regarding the timing of the investment, the larger the cost of the immediate investment, the more the valuation is skewed towards postponing the investment and vice versa. Thus, if there are ancillary benefits to the adaptation strategy independent of the uncertain underlying parameter (climate risk), for example in the case of natural flood risk measures that may provide significant ecosystem services independent of the climate factor flood risk, waiting may not be worthwhile.

In terms of the technical flexibility of an investment, a flexible 'real option' strategy that can be adjusted over time will often be more expensive initially than a supposedly optimal single solution. But the latter might become more costly if the climate change impacts turn out differently than expected leading to premature scrapping or expensive retrofitting (Ranger et al. 2010). Unlike traditional appraisal methods, ROA does not result in a single highest ranked option as an output. It provides flexible strategies along the different climate paths that can be adjusted over time and an explicit valuation of created and destroyed capabilities (Hallegatte et al. 2012).

While relatively widely used for investment projects in the business world (Copeland and Tufano 2004), there are few applications in climate change adaptation. These include mainly large infrastructure flood protection projects such investment in coastal protection (Linquiti and Vonortas 2012; Scandizzo 2011; Woodward et al. 2011). Gersonius et al. (2013) investigated the added value of real option analysis with regard to investments in urban drainage infrastructure in West Garforth, England. The strategy is adjustable and a specific implementation is chosen by observing the actual change of rainfall intensity over time. Other closely related decision-making approaches to ROA include the dynamic adaptive pathways work (Haasnoot et al. 2013), adaptive policy-making (Walker et al. 2001) as well as adaptation tipping points (Kwadijk et al. 2010) and adaptation pathways (Haasnoot et al. 2012; Haasnoot et al. 2011). They vary in terms of how they identify different climate paths, trigger points for action and design plans that can be adjusted as well as how they are presented visually.

Limited application may be related to the complexity of the appraisal process. Probabilities need to be assigned to different plausible climate change paths assuming a science-first approach. However, probabilistic data may not be available for all regions as it is for example for the UK (Murphy et al. 2009) and these depend on different emissions scenarios. Additionally, to provide quantitative results, good data is necessary: methods such as genetic algorithms or dynamic programming that usually require expert knowledge can provide solutions to the objective function. However, ROA can also be applied qualitatively by drawing up a decision tree that outlines different adaptation paths to provide conceptual guidance on the adaptation strategy. Moreover, the short-term nature of decision making and budgeting both in the public and private sector work against the implementation of such long term plans with possible high up-front costs. In addition, the institutional memory of an organisation of collective concepts of how to do things may impede the move towards different strategies.

2.4.3 Robust-decision making

A policy-first (Carter et al. 2001), or also called 'vulnerability-first', 'thresholds first' (IPCC 2012), 'context first' approach (Ranger et al. 2010) is based on the principle of first defining the objectives and constraints of the adaptation problem and its remedies. In a second step their functioning against different future projections is tested to determine the least vulnerable strategy, such as in Robust Decision Making (RDM).

The concept of robust decision making is not new (Matalas and Fiering 1977) and has been used in different variations but it is most prominently linked to the RAND Corporation (Lempert et al. 2003). It was originally designed for decision-making in poorly-characterised uncertainty with a subsequent application to climate change adaptation (Lempert et al. 2006). The approach identifies measures that have little sensitivity to different climate change scenarios by trading off some optimality (Lempert and Collins 2007). Figure 2-4 illustrates the decision-making process of RDM.

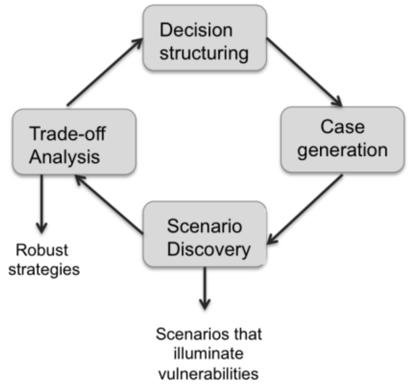

Figure 2-4 Conceptualisation of robust decision-making (Lempert et al., 2013)

First, the problem at hand is structured, i.e. what is the aim of the decision-making process, and subsequently a number of potential strategies are identified. In an application of Lempert and Groves (2010) the current water management plan in the Western U.S. that aims to ensure sufficient and affordable water supply was tested. Possible management options included recycling of water, improved water efficiency and expansion of ground water. It is crucial that the uncertain parameters and their plausible ranges are identified, as these will define the vulnerability of different strategies. For the case study, beside a wide range of climate change scenarios, future socioeconomic conditions, the agency's ability to implement the plan and costs went into the analysis based on climate change projections and expert knowledge for management options. Simulation models are used to create large ensembles (thousands or millions of runs) of multiple plausible future scenarios from the parameters without assuming a likelihood of the different scenarios. The costs and benefits of different strategies are determined with the use of a value function (Lempert and Groves 2010; Lempert et al. 2006; Lempert and Schlesinger 2000). Subsequently, the different strategies are tested against a robustness criterion, which may be that the strategy performs well compared with alternative strategies in many different future scenarios, or a certain cost-benefit measure (Lempert and Schlesinger 2000). For the California study, supply and demand metrics as well as per-unit costs to each of the water supplies (including efficiency) to estimate total costs to the region for consuming and disposing of water were used. In an iterative process, the candidate strategies can be adjusted and fed repeatedly through the ensembles. Accordingly, RDM does not predict uncertainty and then rank alternative strategies, but characterizes uncertainty in the context of a specific decision: the most important combinations of uncertainties to the choice among alternative options are determined in different plausible futures. As a result of the analysis, trade-off curves compare alternative strategies rather than providing any conclusive and unique ordering of options. In California, the trade-off curves also included the (political) effort needed to implement certain measures through weights. RDM thus also considers the precautionary principle by illuminating the risks and benefits of different policies (Kunreuther et al. 2014). Generally, a strategy that performs well over a range of plausible futures might be chosen over a strategy that performs optimally under expected conditions. Other approaches closely related to RDM include Decision-Scaling (Brown and Wilby 2012), Info-Gap (Ben-Haim 2006) and Many-Objective Robust Decision Making (MORDM) (Kasprzyk et al. 2013). They differ in terms of alternative generation, sampling of states of the world, quantification of robustness measures, and sensitivity analysis to identify important uncertainties (see Herman et al., 2015 for further comparison of the approaches.). Interestingly, Kasprzyk et al. (2013) conduct a multi-criteria portfolio analysis within a robust decision making context to provide decision support approach. They present pareto surfaces to decision makers and allow them to decide where on the surface they would like to reside. Figure 2-2 can be interpreted as a MCA pareto frontier where the return will consist of an array of factors.

RDM applied fully quantitatively is very data and resource intensive. For example, for the development of the water management plan in Southern California an investment of between $100,000 (where a simulation model already exists) and $500,000 (where the model needs to be developed) (Hallegatte et al. 2012) was suggested. The development of the simulation models, the metrics, acceptable risks, the benchmark for testing the strategies, as well as plausible scenarios and their upper and lower bounds need to be clearly defined. Choosing all these parameters implies that assumptions about plausible values need to be made in RDM whose range is up to the decision-maker's discretion and may thus introduce a subjective view about the future.

In the literature Groves and Sharon (2013) used RDM to develop a set of coastal risk-reduction and restoration projects in Louisiana, U.S. given a budget constraint. In an application to flood risk management in Ho Chi Minh City's Nhieu Loc-Thi Nghe canal catchment, Lempert et al. (2013) evaluated that the current infrastructure plan may not be the most robust strategy in many plausible futures emphasising the importance of adaptively using retreat measures. A further application includes determining water management strategies such as in Lempert and Groves (2010) and Mortazavi-Naeini et al. (2015).

There are some studies that apply RDM in a simplified form, trading off data requirements while retaining the principle of policy first analysis. A study on evaluating natural flood risk measures in North Yorkshire, UK (Frontier Economics 2013) made an attempt at simplifying robust decision making by reducing the number of climate change scenarios included. Matrosov et al. (2013) use RDM to select portfolios of water supply and demand strategies in the Thames water system, UK, simplifying the methodology by considering a smaller number of options but considering different uncertainties (hydrological flows as well as demand and energy prices). Bonzanigo and Kalra (2014) showed that the data and tools typically used in classic economic analyses such as CBA can be used while applying the principles of RDM with an application to an Electricity Generation Rehabilitation and Restructuring Project to improve Turkey's energy security. Prudhomme et al. (2010) integrated the idea of vulnerability first by testing the sensitivity of catchment responses to a plausible range of climate changes instead of focusing on time-varying outcomes of individual scenarios. This includes scanning over a range of relevant climate parameters to identify the amount of change that would cause a proposed policy to fail which can the be combined with model projections for plausibility (Brown and Wilby 2012; Groves et al. 2013).

2.4.4 Robust options by design: No/Low Regret

A further way of circumventing the difficulty of characterising uncertainty is the generation of alternatives that are robust due to their characteristics irrespective of the approach to appraise them. These options may be an alternative in the short term to handle climate change uncertainty. No regret options (also labelled early benefits (Fankhauser and Soare 2013), avoid the necessity of quantifying climate change impacts. Instead these robust options will yield social and/or economic benefits irrespective of whether climate change occurs delivering benefits now and building future resilience (Watkiss and Hunt 2014). The options are usually specific to the adaption problem. Typical examples include fixing leakages in water pipes or water use efficiency improvements in areas that already suffer from long-run drought and increased demands independent of climate change (Hurd 2008). With quickly visible benefits, decision makers are likely to implement no-regrets options more readily in contrast with other less robust adaptations. Indeed, no-regret options are often considered best practice and should be implemented in any case as a first step towards increased resilience. Assessing the net benefits of such adaptation options can be carried out with CBA, CEA or MCA.

While the concept of no regret options initially appears relatively uncontroversial, it is unclear what low regret options comprise (Preston et al. 2015). They may have low costs, some benefits now and in the future, or they may be options that lead to future benefits or offer benefits across most climate scenarios (Watkiss and Hunt 2014). Different (sometimes controversial) examples include building adaptive capacity, such as measures to deal with heat stress in cities and irrigation. However, irrigation may become a maladaptation if too much water is extracted or resources might be wasted if heat stress is over-estimated when traditional predict-then-act approaches for appraisal are applied. Watkiss and Hunt (2014) argue that potential low-regret measures need to be framed in an iteratively adaptive way i.e. integrating the idea that we know best about the near future and less about the distant future. For instance, soil and water quality improvement are low regret options handling current climate variability; investing in upgradable infrastructure with respect to medium-term climate change, and on-going research on climate change with respect to the distant future.

2.4.5 Reduced decision-making time horizons

Another alternative to reduce uncertainty includes the generation of adaptation alternatives with reduced decision-making time horizons. The aim is to be able to adjust the action over time through several short time horizons decisions based on the assumption that this might be less costly than few large long-term decisions. Examples include lower quality and thus cheaper housing in flood prone areas (although this may also be a maladaptation in terms of the wasted resources and energy used). In forestry, shorter rotation species can be chosen to reduce time horizons as neither safety-margins nor reversibility are feasible (Hallegatte et al. 2012). Similarly, some soft options can reduce decision-making time horizons, for example the use of insurance markets to protect against flooding in the short term (UNFCCC 2009). The robustness here lies in the fact that the features of the adaptation options will likely provide benefits in the short term. Shortening the decision time horizon converts deep uncertainty to potentially quantifiable uncertainty that can then be assessed with appraisal methods that aim for optimality. The strategy can then be revised and adjusted in the future when more information might be available about climate change impacts. However, similarly to low regret measures the question of which measures actually fulfil the reduced decision time horizon characteristics arises, and related to this the extent to which traditional appraisal methods can be employed.

2.5 Which method for which situation?

It is clear that that different approaches will work well in different circumstances, depending on the characteristics of the adaptation options being considered, the data available, and the time and skills available to the decision maker.

To help identify the appropriate method for a particular adaptation project, Figure 2-5 presents a simple framework encapsulating the mechanisms of robust decision-making approaches under uncertainty, helping to identify which method will perform well contingent on the characteristics of the available options. This framework presupposes that an area of vulnerability and the adaptation question has been clearly framed, whether this relates to investment in adaptive capacity or infrastructure measures. The more concrete and tangible the measure will be, the more easily the framework can be applied. For example, finding an appropriate tool for a flood risk management option will be more straight forward than for the adaptive capacity option of investment in further climate research as the questions are tailored to specific costs and benefits. Also, the available data and their format need to be known (Ranger et al. 2010). It should be clear that any chosen adaptation option should not be in conflict with (emissions) mitigation measures (Smith and Olesen 2010). The framework also reflects that robust decision-making approaches under uncertainty may not always be feasible and traditional appraisal methods may still work best in some situations due to data limitations and the nature of the adaptation options.

To determine the most appropriate method the adaptation options are characterised according to their scale, level of uncertainty and data availability. The questions must be answered with the available adaptation options in mind. Some adaptation options may be suited to two or even three appraisal methods.

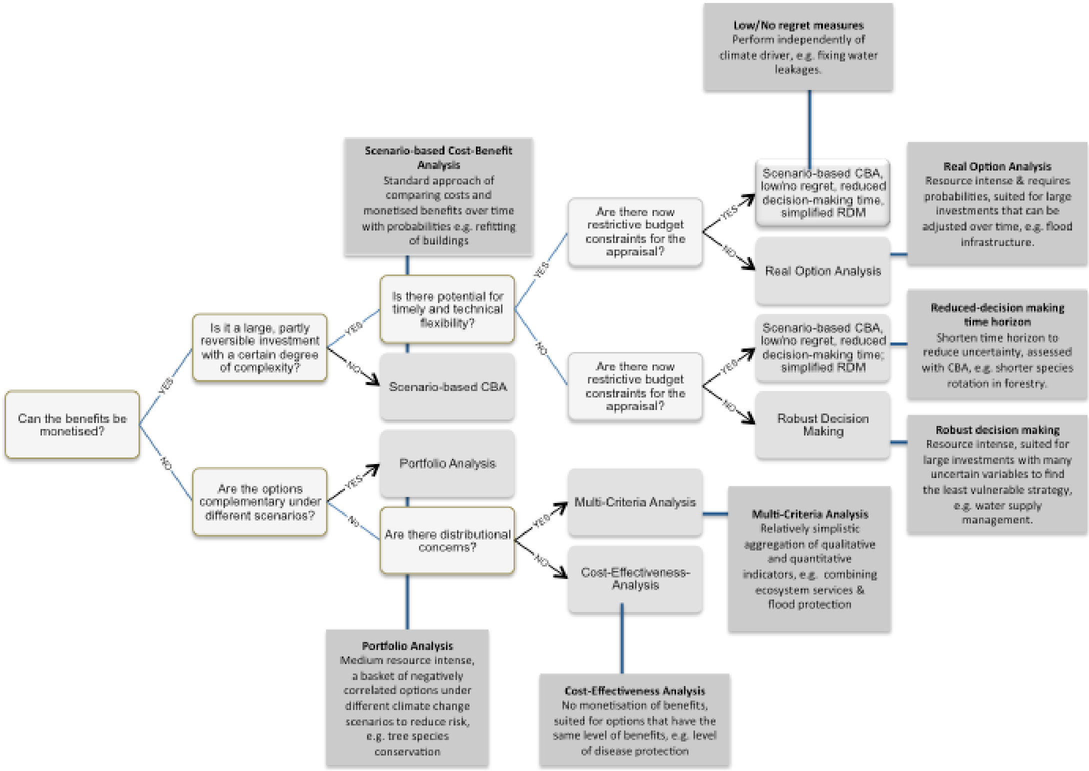

Figure 2-5 Finding a suitable appraisal method for adaptation options (Adapted from DEFRA (2013a))

2.6 Discussion

It is clear that different appraisal methods work well for different adaptation problems. The framework highlights that RDM and ROA, which are relatively resource- demanding might not be feasible if there are budget constraints: either a simplified application of the methods or a traditional appraisal method may need to be used. For example, assuming benefits can be monetised (step 1) but the potential investment is relatively small (or reversible) (step 2), the expenditure for a robust appraisal may not be justified. If the investment is large and (partly) irreversible and timely and technical flexibility exists (step 3), ROA may be suited, providing there is no major constraint on budget/time for the appraisal (step 4). If this is the case, one may have to revert to one of the less resource intense appraisal approaches (step 5). At the same time, while it is important to choose an appraisal method matching the characteristics of the adaptation options, it is also crucial to recognise that different methods may resonate with different audiences, as they employ different means of communicating decision options and uncertainty. For example, MCA is useful for stakeholder inclusion and can be easily explained to a non-technical audience but the inclusion of climate uncertainties will remain simplistic. Whereas interpreting the results of RDM can be demanding but will provide a comprehensive picture of the various vulnerabilities of strategies. It should be noted that traditional decision-making approaches lead to specific actions that ought to be implemented based on decision criteria founded in rationality (e.g. highest positive NPV) whereas some of the robust decision-making approaches under uncertainty provide decision support instead (Lempert 2014) Using the definition from the National Research Council (2009), this represents "the set of processes intended to create the conditions for the production and appropriate use of decision-relevant information." In particular RDM but also PA focus on the goal of providing actionable information to decision makers, who will then make their own decisions (e.g. trade-offs between options).

Second, despite delivering robust adaptation options and strategies across a range of climate change scenarios, robust methods under uncertainty still require assumptions about climate change scenarios. This seems contradictory at first, as robust methods under uncertainty are designed to handle situations of deep uncertainty (i.e. the absence of reliable data), but for a meaningful analysis it is necessary to clearly specify the range of uncertainties (to the extent this is possible).

ROA and PA are based on predict-then-act, science-first foundations. Both methods require impacts first, usually employing probabilities to describe different but nevertheless limited numbers of climate change scenarios and the adaptation strategy is optimised given the potential climate variability. Both methods then deliver robustness by integrating different climate change scenarios when appraising and simultaneously developing adaptation strategies: ROA by creating adjustable adaptation strategies for different climate change scenarios and PA by implementing a basket of adaptation options suited to different climate change scenarios. Nevertheless, the choice of the climate change scenarios considered and possibly also the probabilities for different climate change outcomes are the subjective decision of the analyst and need to be justified. Similarly, for policy first approaches such as RDM that start out with candidate strategies and not impacts it is still necessary to define the range of climate change risks the strategies are tested against. While considering these different climate change risks can help to explore the scenario space further, it nevertheless implies to an extent a valuation of how extreme the climate changes might turn out to be. Moreover, depending on the concrete adaptation problem at hand considering a very wide band of climate change scenarios can lead to a least vulnerable solution that has low benefits in the climate that actually occurs, as the benefits are considered across scenarios. This point highlights that there is a trade-off between optimality (i.e. choosing a strategy that perfectly matches a certain state of the world) and robustness, and we do not necessarily face a binary choice between an optimal or robust strategy, but rather the objective is to determine the lowest level of trade-off between optimising returns and robustness (Lempert et al. 2003). Weaver et al. (2013) point in this context to the importance of using climate models more intensively and to explore complex systems and their uncertainties. This does not necessarily imply improving projections, which will always suffer from some uncertainty (Dessai et al. 2009), but for example considering a larger set of climate models (Rajagopalan et al. 2009), comparing results from downscaling techniques (Steinschneider et al. 2012), or running a deeper sensitivity analysis to various components in the modelling chain (Dessai and Sluijs van de 2007), which could ameliorate the use of climate models. The IPCC suggests applying a science-first approach when uncertainties are shallow, and a policy-first approach when uncertainties are deep (Jones et al. 2014).

Third, robust methods under uncertainty are still relatively novel in the academic and policy agenda for adaptation. It is therefore not surprising that planners are as yet unfamiliar with the application of these methods. It takes time to become familiar with new concepts, moving away from traditional appraisal methods. But it is also true that the application of robust methods under uncertainty is in general more complex and time-consuming than carrying out a cost-benefit analysis. Robust methods under uncertainty often require a large amount of (monetised) data and the actual appraisal process might involve relatively complex mechanisms. Examples include the application of genetic algorithms in real option analysis (Gersonius et al. 2013), or solving the value function in robust decision making (Lempert and Groves 2010). Portfolio analysis requires the specification of standard deviations of the different adaptation options. A simplification of these approaches is needed to make them more accessible to a broader audience. Indeed, real option analysis has already been simplified for its application beyond financial options to real investment projects (Cox et al. 2002) and this could potentially be further developed for adaptation. The development of different flood defence options for the Thames Estuary 2100, England (Environment Agency 2011) used the principles of real option analysis by applying iterative adaptive management: the plan is flexible to a changing climate because interventions can be brought forward in time, alternative pathways can be included, and existing structures can be extended. While the analysis within the different components was carried out with CBA, the overall project was designed in a flexible way to allow for adjustments. Haasnoot et al. (2013) use the principles of ROA by exploring and sequencing a set of possible adaptations based on external developments in their frameworks of 'Adaptive Policymaking' and 'Adaptation Pathways' as a guidance for decision-makers.

Similarly, there are some studies that apply robust decision making in a simplified manner as mentioned above (Bonzanigo and Kalra 2014; Frontier Economics 2013). Indeed the body of policy first approaches (including RDM) appears to have the greatest potential to become mainstreamed among the body of robust methods under uncertainty to decision-making. The principle of starting out with strategies and testing them against uncertainties can be simplified at many points in the analysis. This includes the range of climate scenarios and other uncertainties as well as the number of strategies. While there is also strong academic interest in the other robust decision-making approaches under uncertainty, particularly real option analysis, reflected in the range of studies in this field, it is not obvious that they can be simplified as well as policy-first approaches. Even more importantly, policy-first approaches can be applied well to most adaptation challenges if the options are well differentiated - not necessarily the case for the other approaches.

Despite its advantages however, the application of simplified RDM is also a learning process: from understanding how to structure a robustness analysis, to learning software that aids in scenario discovery, to interpreting the results of scenario discovery, to communicating the idea of trade-offs to stakeholders (Bonzanigo and Kalra 2014).

In summary, the development of simpler and more generic toolkits for the quantitative application of robust decision-making methods under uncertainty is still in its relative infancy. Thus, the relative size, impacts and risks of the adaptation project need to be taken into account when choosing a decision-making method. While it is doubtlessly worthwhile to apply quantitatively robust methods under uncertainty for long-lived large investments, for example in infrastructure or spatial planning, decision-makers might resort to no/low regret measures or reduced decision-making time horizon options where feasible in the short term, which can be assessed with CBA as emerges from figure 2-5.

It should also be clear that robust methods under uncertainty cannot accommodate challenges that are intrinsic to any appraisal method. This includes the question of using an appropriate social discount rate when valuing the benefits accruing for future generations (Pearce and Ulph 1998) but also the challenge of valuing environmental goods in monetary terms (Garrod and Willis 1999). More generally all methods are based on incremental changes. Broader questions such as the socio-economic assumptions on which modelling of a distant future should be based or the policy goals of decision-makers in the future (Lempert and Groves 2010; Wise et al. 2013) are out of reach for these methods. Certainly, climate change is often only one driver when decision-makers consider investment decisions, implying that the costs and benefits need to be studied in a wider context. For example, the demand side is crucial for water supply beyond climate change.

Finally, it should also be noted that further factors may hamper the adaptation option appraisal and ultimately the implementation of adaptation action, including behavioural barriers (Adger et al. 2009; Grothmann and Patt 2005), the lack of institutional leadership and cooperation (Moser and Ekstrom 2010), historical path dependency (Abel et al. 2011), or the lack of financial and human resources to implement adaptation actions (Bryan et al. 2009) amongst others.

2.7 Conclusion

Where planned adaptation to climate change is necessary, decision makers need to move away from striving for solutions that assume an investment today will necessarily match the actual state in the future. Uncertainties surrounding climate change projections and impacts, as well as changes in emissions in the future, mean that these assumptions will be invalid. Taking these uncertainties on board, decision-makers should consider more robust decision-making methods under uncertainty instead of standard cost-benefit analysis, cost effectiveness analysis or multi-criteria analysis. Robust approaches do not assume a single climate change projection, but integrate a wide range of climate scenarios through different mechanisms to capture as much as possible of the uncertainty on future climates. This chapter presented a range of robust methods under uncertainty, describing their characteristics, applications and limitations: while providing performance across a range of climate change scenarios, they may yield lower overall performance if compared with the alternative strategy under the actual climate outturn, and a well-defined scenario space is indispensable. Moreover, decision makers need to balance the resources required for employing the methods with the added value they can offer. The body of policy first approaches appears to have the greatest potential to be mainstreamed. They can be simplified at many points in the analyses and applied to a wide range of adaptation problems. Academia has an important role to play in this by further improving the accessibility and demonstrating the general applicability of these methods, and by developing more generic toolkits. This dissertation uses this result, the need for simplification in robust methods under uncertainty, in the subsequent section and chapters by suggesting and providing specifically such simplified applications to appraise adaptation options.

2.8 The agricultural and livestock sector and climate change

Agriculture is especially vulnerable to climate change due to its dependence on climate-sensitive natural resources (Howden et al. 2007). Climatic changes are already being experienced: across Europe, the average decadal temperature for 2002-2011 was 1.3° C ± 0.11°C above the 1850–1899 average and since the 1950s annual rainfall has increased over Northern Europe and decreased over southern Europe, as well as an increase in extreme conditions. Temperatures are projected to rise by between 1°C and 4°C per century across Europe, and precipitation to increase in Northern Europe and decrease in Southern Europe (IPCC 2014b).

The projected changes, including the effects of climate variability and extremes, will have direct effects on livestock productivity, either on the animal directly (e.g. through heat stress) or indirectly through effects on crop production and the disease vectors to which the livestock are exposed. For example, increases in winter temperature will lengthen the thermal growing season in regions where temperature constrains crop growth during winter. But higher temperatures during the growing season may result in yield reduction as experienced during the heat waves of 2003 and 2010 when grain losses reached 20% in Europe (IPCC 2014b). The livestock sector contributes substantially to the European economy (€169.5bn in 2013), being 41% of total agricultural activity (FEFAF 2013) and creating employment among the 10 million people working full-time and 25 million people working part-time in agriculture in Europe (European Commission 2013b). Further, demand for livestock products is likely to increase in the future, particularly in developing countries (Thornton 2010). Thus, given the economic importance of the livestock sector in Europe, minimising the impact of climatic changes on its output through effective and strategic implementation of adaptive practices will be critical. Adaptation options are wide-ranging, from incremental changes in management in current systems, to long-term structural and transformative changes in the farm as well as the sector as a whole, with a growing body of research identifying options and their effectiveness (e.g. Renaudeau et al. (2012) and Hoving et al. (2014)).

In the second part of chapter 2, we explore the applicability of different economic appraisal methodologies for livestock adaptation options, given the uncertainty surrounding climate impacts. We take recognised adaptation options available to the livestock sector, outline their costs and benefits and provide recommendations on which appraisal method is most appropriate given the characteristics of the options. Thus, this section of this dissertation provides practical advice on how and when to apply the robust decision-making methods under uncertainty identified and discussed in the first part of chapter to the sector of livestock agriculture. To our knowledge this summarised classification of appraisal method to adaptation option has not previously been carried out and we believe provides a useful summary of ways to approach adaptation appraisal in the livestock sector. Three detailed examples of the robust methods under uncertainty to illustrate their application in practice are then provided. The focus is on farm decision-making within European livestock but the principles can be applied to a range of production systems.

2.9 Economic appraisal, risk and uncertainty

Uncertainty regarding future climate changes, together with the imperative to make adaptation decisions in anticipation of these future climates can leave decision-makers struggling to understand what the appropriate course of action might be, particularly with adaptation actions that require significant investment. Fortunately, many of the adaptations available to the agricultural sector do not involve long time horizons. Economic approaches based on expected values such as cost-benefit analysis (CBA) and expected utility are generally suited for short-term decision-making where probabilities can be attached to outcomes or changes are only implemented after the change has occurred. Expected utility approaches are useful to consider risk attitudes under increased weather variability which we expect to see more under climate change (IPCC 2012). Risk aversion may be of increasing importance in such contexts. But in some cases longer time horizons cannot be avoided – either through the adaptation requiring a longer time to be fully effective (long lead time), or because once it has been adopted is difficult to reverse (long life time).

However, if there is deep uncertainty as for projects with long lead times or long life times, CBA does not cope well and choosing an adaptation that is unsuited for the actual climate outturn would imply an inappropriate investment. The robust decision-making tools under uncertainty discussed in the first part of chapter 2 may be more suited.

We focus on the identification of adaptation options and application of appropriate appraisal methods to the livestock sector. Figure 2-6 shows that for decisions with a short lead time/planning time standard economic approaches such as CBA are appropriate as those can be easily reversed. More robust methods under uncertainty should be employed for longer time scales when irreversibility plays a role due to the longer planning and lead-time under climate change uncertainty.

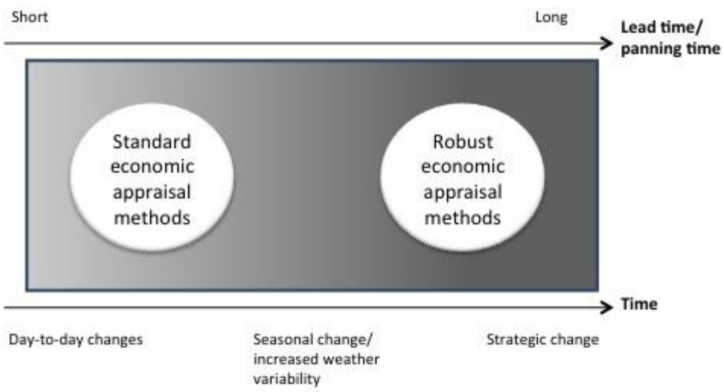

Figure 2-6 Lead/Planning time and appraisal method

2.10 Adaptation options in the livestock sector: appropriate appraisal methods

In this section we identify a range of possible adaptations and group them by their lead and lifetime characteristics, in order to clarify the methodological approaches most appropriate for each option. The adaptation options considered were previously identified for European livestock agriculture in Wreford and Dittrich (2015) and are based on impact categories identified from literature (Iglesias et al. 2012; IPCC 2014b). The analysis was carried out by a small group of four experts in the area of adaptation farm systems to climate change. The different adaptation options were discussed among the experts and the relevant timeframes for the options were identified as well as the relevant costs and benefits of each measure.

2.10.1 Short life time adaptations

As previously stated, many of the adaptations in the agricultural sector can be made in response to observed changes in climate, requiring little lead-time and able to be easily reversed. Many of these adaptation options involve managerial changes, such as adjustments to the timing of operations, the movement of stock in response to immediate conditions, the management of feeding and grazing and disease and pest control. They also include soil and water management and conservation. The options are also often flexible and/or reversible, with few longer-term implications, such as changes to the grazing regime or the installation of small-scale water storage facilities (Payen et al. 2012). A comprehensive range of adaptation options are identified in table 2-1 and their types of costs and benefits summarised so that the appropriate appraisal option can be recommended. Options with short lifetimes such as these managerial changes are generally suitable for appraisal by either (expected) formal or informal CBA (Scottish Agricultural 2013)[4].

2.10.2 Long life-time adaptation: robust appraisal methods

Other types of adaptations will require either a longer lead-time in their planning, or will have long life-times, where the implications of decisions made now will be long-lived, and where uncertainty regarding the future climate can create a barrier to decision-making. These types of adaptations will require more robust appraisal approaches for efficient decision-making. In table 2-1 we identify which of the three robust approaches discussed previously would be most suitable for a range of potential adaptation options in the livestock sector. We also include measures that would be made in response to increased weather variability, which may not necessarily have long lead times but address a range of future climates and hence require an appraisal method which takes the increased range of outcomes into account. The types of adaptations where portfolio analysis is most appropriate typically involve diversification or changing to a less productive species (animal or crop). Adaptations that involve the a capital investment often in the construction of a building or infrastructure are more suited to Real Options Appraisal, while Robust Decision Making is ideal when a range of differentiated strategies for adaptation are available.

[4] Many of these options would be appraised informally by the individual farmer without a quantitative appraisal, however we can still expect the farmers to weigh up the (expected) costs and benefits of any action they take.

In section 3.4.2.1 to 3.4.2.3 we take one adaptation example for each of the robust appraisal methods and describe in detail how the appraisal methods would be applied in practice.

Type of appraisal	Types of adaptations	Further explanation
CBA	Move herds to more suitable conditions from waterlogged fields, extreme dry situations and from extreme heat or cold.	Benefits include maintained productivity; costs include management & labour (If no shelter exists, long-term adaptation will be to construct more housing, see further in table).
	Change breeding and shearing patterns. For animals kept outside, e.g. sheep, the time of lambing and shearing can be adapted to the seasonal weather conditions.	Benefits include maintained productivity (e.g. through avoidance of heat/cold stress); costs include labour.
	Adjust stocking density to avoid poaching and overgrazing; to cope with a reduction in available food; to minimise disease outbreaks; to cope with heat stress in intensive conditions (e.g. transport)	Benefits include pasture preservation; avoided costs of disease outbreaks; maintained productivity (per animal); costs include reduced total production.
	Ensure access to water to aid thermoregulation.	Benefits include maintained productivity; costs include management/labour costs.
	Adjust timing of animal transport to avoid heat/cold exposure.	Benefits include maintained productivity & avoided mortality; costs include management/labour costs.
	Adjust diet to ensure sufficient dealing with hot weather. Ensure energy requirements are being met if the heat reduces total feed intake; supplements can also assist	Benefits include maintained productivity/reduced mortality; costs include cost of feed/supplements, labour.
	Vaccination for climate related diseases.	Benefits include maintained productivity/reduced mortality; costs include labour; purchase of vaccines.
	Conserving surplus production of feed supply. Seasonal variations in roughage feed supply are buffered by conservation methods	Benefits include continued production; costs include foregone income from sale of surplus feed.
	Supplemental feeding in situations of a loss in forage quality and quantity.	Benefits include maintained productivity/reduced mortality; costs include purchase of supplemental feed.
	Restoring degraded land to increase agricultural output or counteract decreases in output in other areas.	Benefits include increased output; costs include initial investment and on-going maintenance, loss of output where this involves leaving the land fallow.
	Apply crop/fallow rotation.	Benefits include increased soil fertility and yield due to N fixing in soils in the medium/long term. Also improved water holding capacity thus reducing drought and pest outbreaks. Costs include management changes.

Table 2-1 Adaptation options and the identification of their relevant costs and benefits as well as of a suited appraisal method

Type of appraisal	Types of adaptations	Further explanation
CBA	Optimal use of fertilisers and manure.	Benefits include improved productivity and potential increased resilience to climate change; costs may include increased fertiliser costs (potentially also indirect costs of increased GHG emissions).
	Set clear water use priorities. Ensuring the most important water demands are covered such as drinking water for animals and basic irrigation for crops.	Benefits include avoided costs of purchasing water; or implications of stock & crop dehydration. Costs include foregone profit from lower prioritised uses.
	Increase water use efficiency.	Benefits include avoided costs of purchasing water; or implications of stock & crop dehydration. Costs include foregone profit from lower prioritised uses.
	Reduced/zero tillage in order not to disrupt the soil.	Benefits include higher yields due to improved soil fertility and water retention. Costs include the loss of crop residues for animal feed.
	Improve field drainage water absorption capacity to minimise waterlogging.	Benefits include avoided soil compaction & stock health costs; negative crop impacts. Costs include machinery & maintenance.
	Small-scale reservoirs on farmland to collect rainwater and technical improvements in irrigation equipment.	Benefits include production continuity; costs include installation, maintenance, and potential foregone profit from land taken out of production.
	Reduce run-off through contoured hedgerows and buffers.	Benefits include avoided erosion and the costs of planting of and more difficult field access due to hedgerows/buffers.
	Use of precision agriculture techniques.	Benefits include improved efficiency; costs can include machinery & equipment.
	Insurance	Benefits include avoided expected financial loss; costs include premiums.
	Water management practices. Terraces, mulching, ditches and grass strips can be used to conserve soil water. Timing of water use such as irrigation at night, water efficiency and conservation strategies through separating dirty/clean water can be adjusted.	Benefits include avoided costs of purchasing water; or implications of stock & crop dehydration. Costs include machinery, maintenance & labour.

Table 2-1 continued

Type of appraisal	Types of adaptations	Further explanation
CBA	Incorporation of crop residues	Benefits include soil fertility and water retention through building organic matter. Difficult to quantify due to the long-term nature of changing soil C. Costs include the loss of crop residues for animal feed; labour & machinery.
	Additional weed/pest control.	Benefits include avoided weed & pest outbreaks; costs include weed & pest control products; labour; indirect costs of increased nutrient leakage, pesticide resistance.
	Shelter belts	Benefits include shade and protection from wind, potentially increased yield & decreased erosion. Costs include more difficult access to fields, labour, equipment, maintenance & potentially foregone profit from land taken out of production.
	Advisory service for farmers	Benefits include increased adoption of these measures and thus avoided losses and maintained production of the sector. Costs include the administrative costs of establishing advisory services (although existing services may be able to incorporate adaptation advice), labour.
Portfolio Analysis	Changing high yield/productive breeds for lower yielding/less productive more heat tolerant breeds.	Heat tolerance/productivity can be traded off through a 'basket' of breeds.
	Cover crops to improve soil structure and to reduce erosion due to wind and rainfall.	Cover crops can be sown on some fields and not on others depending on the cost for cover crops and time available to sow, i.e. a basket of cover crops. This is not a long-term adaptation option but can help to improve soil structure in a given climate more efficiently.
	Grass and legumes can be combined in a way to trade-off productivity and heat tolerance.	Grass-legume swards have important yield advantages compared to monocultures. Legume species have higher temperature optima than grasses. Other potential benefits: On soil structure due to deep rooting systems and for carbon sequestration (the latter is partially dependent on the change in reseeding that may be required). Improvement of productivity on crops/grasslands through more efficient fertiliser use due to reduced requirement for N by the legumes.

Table 2-1 continued

Type of appraisal	Types of adaptations	Further explanation
Portfolio Analysis	Combining different crop varieties to trade off productivity and adverse events resistance.	
	On a regional/national level: portfolio of pastures and crops according to land capability.	
	Replace more productive sheep breeds with hardier breeds.	
	Replace/combine high productivity crop varieties with more pest-resistant varieties.	
Real Options Analysis	Hard flood risk defences to protect livestock and agricultural land.	The defences can be scaled up over time in the least costly way if the potential full design is considered now.
	Natural flood risk management (NFM) measures to protect livestock and agricultural land.	The defences can be scaled up over time in the least costly way if the potential full design is considered now.
	Housing to protect animals from heat	The possibility of later adding cooling pads, fans systems, water sprays/misters to buildings and/or outdoor areas (e.g. collecting yards).
	Large-scale irrigation for improved water supply/farm scale reservoirs.	Can be scaled up over time in the least costly way if the potential full design is considered now.
Robust Decision Making	Holistic water basin management to identify the least vulnerable strategies to meet the water demand.	Water flow related to climate change scenarios as well as benefits/costs of the options under climate change.

Table 2-1 continued

2.10.2.1 Adapting to heat stress –application of portfolio theory

All animals have a range of ambient environmental temperatures known as the thermal neutral zone and exceeding this range negatively affects livestock performance. Heat stress starts at the upper critical temperature of this zone. The animal cannot dissipate an adequate quantity of the heat to maintain the body's thermal balance (Moran et al. 2009). Figure 2-7 illustrates the relationship between temperature, humidity and heat stress (Wiersma 1990).

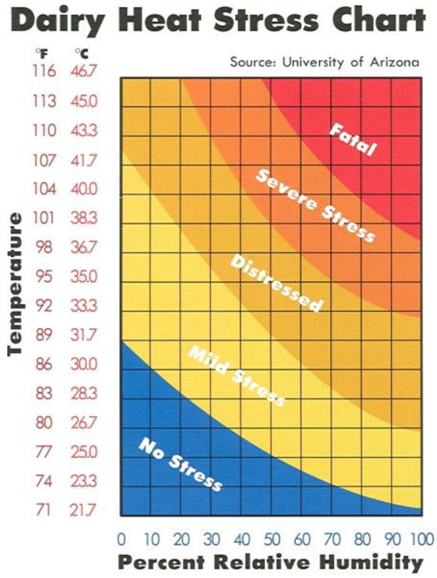

Figure 2-7 Chart of the severity of heat stress in dairy cattle (Wiersma 1990)

Heat stress causes productivity losses or even mortality and thus incurs economic costs to the industry. St-Pierre et al. (2003) estimated that total losses across animal classes averaged \$2.4 billion in the US annually if there is no heat abatement.

Higher yielding animals produce more body heat due to their greater metabolic activity (Settar et al. 1999; West et al. 2003), implying that there is a trade-off between productivity and heat tolerance (Hoffmann 2010). But to increase profit, more productive animals are sought and we may thus expect heat stress to become more of a problem in future due both to climate change and trends in breeding.

While this trade-off between productivity and heat tolerance can apply to a range of livestock species, we focus here on dairy cattle due to data availability. Similar applications can be developed for pigs and poultry (see table 3-2 for relevant references).

We suggest the application of portfolio theory (PA) to appraise adaptations to combat heat stress in livestock. The underlying concept of (PA) is analogous to combining different stock market shares in a portfolio to reduce risk by diversification (Markowitz 1952). Our approach to address heat stress in livestock is to diversify the breeds in a particular herd to reduce the risk of heat stress while trading off some productivity. Having a number of high productivity animals in the herd with low heat tolerance levels and a number of lower productivity animals with high heat tolerance will achieve this objective. It should be noted that this is not an adaptation to long-term temperature changes (as the productive life time of a dairy cow usually does not exceed five years), rather it is an adaptation to increased variability in climate due to climate change.

The adaptation choice (breed composition) is determined by maximising benefits (measured through a productivity metric such as milk yield) given the decision maker's risk affinity (*i.e.* willingness to accept a lower level of heat tolerance). Alternatively, given a defined benefit of the adaptation options, risk is minimised across all adaptation options. Equation 2 specifies an example minimisation problem.

$$\text{Min}\, w^T \sum w\,,\ subject\ to\ \sum_i w_i = 1, w_i\ > 0\ for\ all\ i, and\ E[R]w = \mu \qquad (2)$$

where w_i are the weights of the portfolio of breeds, T is the transpose operator, Σ is the covariance matrix of R, E[R] is the expected return (milk yield) of each breeds and μ is the target expected return. A higher return is associated with a higher risk. A portfolio is best balanced if the co-variances of the assets are negative, off-setting the risk under different scenarios. In other words, low return on one asset will be partly offset by higher returns from other assets during the same period. This applies directly in the livestock case. The higher the productivity of an animal, the lower the heat tolerance and vice versa. The benefits can be expressed both in monetary and non-monetary terms, for instance as milk yield or price obtained per litre milk. The challenge is to relate the climate change scenarios directly to heat stress and thus to return. Using UKCIP02 data (probabilistic climate data for the UK), Moran et al. (2009) calculated the maximum temperature humidity index (as seen in figure 2-7) under different climate change scenarios using maximum monthly temperatures. Each class of animal was assigned a THI threshold based on empirical studies above which that class of animal begins to suffer from heat stress. Subsequently, the data can be related to milk loss in kilograms per day and based on the number of days where the threshold is exceeded, milk loss per year can be calculated. Based on this, the return (milk yield) for each breed can be calculated under each climate change scenario. Average expected returns then need to be calculated across all chosen climate change scenarios by attaching probabilities to the scenarios which is also a possible short coming of the method as it is not clear that probabilities can be attached with confidence to climate change outcomes (Hallegatte et al. 2012). Further data that is required includes the co-variances between the returns of the different breeds.

Given this data, the problem can be solved either as a minimisation or a maximisation problem with a constraint. For the former as specified in equation 2, risk is minimised (based on the co-variances of the assets) for a given return. A so-called efficiency frontier can be derived as in figure 2-8 if the minimisation problem is solved for a range of target returns. The efficiency frontier identifies different portfolios for the number of dairy cows that should be purchased proportionally as part of the herd (*i.e.* the portfolio weights). PA assumes that the decision-maker is risk averse and the choice of a specific portfolio on the efficiency frontier depends on his/her risk tastes (i.e. their type of utility function). Thus, for example under increased weather variability, a more risk-averse farmer may opt for a portfolio with an overall lower expected return but relatively low risk, i.e. a point in the left bottom corner on the efficiency frontier in figure 2-8.

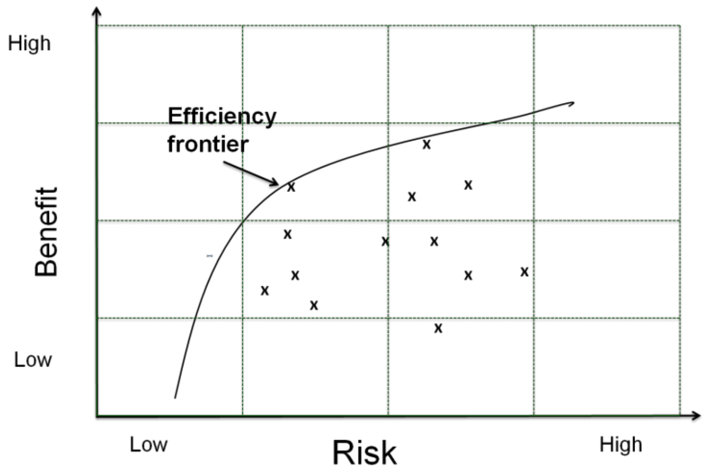

Figure 2-8 Graphical representation of different feasible portfolios

2.10.2.2 Adapting to flood risk – applying real options analysis

The frequency and intensity of extreme events is likely to increase as a result of climate change (Schär et al. 2004; Stott et al. 2016). Flooding can pose a threat to livestock in two ways: first, directly by threatening the safety of animals, both housed or in fields. Second, indirectly by damaging forage in the form of pastures and crops used to feed livestock, and damages to farm buildings, machinery and other assets. As a consequence, additional forage may need to be bought in by the farmer and assets repaired at potentially high cost. In automated systems, waste management systems can be damaged leading to increased exposure to pathogens and risk of disease or threaten water quality (Schmidt 2000). In monetary terms, storms and floods are already the most frequent and costly weather-related disasters in Europe and accounted for 77 per cent of the economic losses caused by extreme weather events between 1980 and 2006 (CEA 2007).

Building flood risk mitigation measures can help to alleviate this problem. The measures can be both standard 'hard' engineering solutions such as flood walls but also natural flood management (NFM) measures such as afforestation along streams, rivers and field edges to slow down peak flow, restoration of flood plains and retention ponds for water. Hard engineering solutions and to an extent soft NFM measures involve long-lived decisions with high sunk costs that are likely to be sensitive to climate change uncertainties.

If the frequency of floods changes substantially, *i.e.* a flood that occurs in the current climate on average every 50 years may occur in the future on average every 35 years, flood mitigation measures can prevent severe damage and associated costs. Uncertainty about the future means farmers may be unsure whether to invest in building flood risk mitigation measures, and risk over-adapting if extreme events do not change sufficiently in frequency to justify the action. In this situation, a ROA may enable the farmer to make a more informed decision.

In the context of flood adaptation measures this means starting out with a relatively small flood adaptation measure and scaling it up over time if necessary. However there is a trade-off as additional investment comes with fixed cost, therefore continuous investment is not the most economically efficient solution either (Van Dantzig 1956).

For a ROA model that can either minimise costs (as an extension of cost-effectiveness analysis) or maximise benefits (as an extension of cost-benefit analysis) the following steps need to be carried out. Note that the specific solution will vary depending on the problem at hand. ROA also assumes risk neutrality such as CBA and CEA but extends both by adding the option of learning instead of having to make a now or never decision.

In a first step, climate scenarios for the area in question are required, specifically rainfall data. The UK Met office (Murphy et al. 2009) for example, provides a dataset with historical rainfall data across the UK which is perturbed for a range of climate change scenarios. This data needs to be further processed as transition probabilities need to be assigned to different plausible climate change paths. Obtaining such transition probabilities for different time paths can prove challenging such as for PA as this requires attaching probabilities to climate change scenarios and subsequently probabilities on how to move from one climate change path to another. The probabilities have been be obtained with the same formula as in the financial option model which is based on the assumption that the logarithm of the underlying uncertain parameter, here rainfall, follows a stochastic process called geometric Brownian motion (GBM) (see Cox et al. (2002) for an overview). This process was used by Gersonius et al. (2013) and Linquiti and Vonortas (2012). Moving window processes have also been applied (van Der Pol et al. 2015). In a next step the climate data needs to be linked to a hydrological model. The exact hydrological data needed will depend on the specific question and the level of hydrological detail that is required. For a cost-effectiveness application, a constraint such as a specific flood protection standard may be defined. For a cost-benefit analysis, a damage module needs to be included. As a minimum, the model needs to measure discharge without the flood mitigation measure and with different implementations of the mitigation measure under different peak flows. The aim is to relate different levels of peak flow to different levels of discharge subject to different levels of implementation of the flood mitigation measure. In a subsequent step, the economic optimisation model is added. For the economic model, there will be a cost-benefit formulation to be maximised (or only a cost function for CEA to be minimised). Costs comprise the design, land, construction, and maintenance costs of which some are incurred in the present time period, and others are delayed or avoided altogether. Maintenance costs depend on the specific flood mitigation measure. Benefits are avoided damages. Finally, the decision on when to exercise the option to scale up the flood mitigation measure must be made. The decision criteria can be tailored to the requirements of the problem: once a certain damage has been exceeded with a certain probability, or once a pre-defined standard (e.g. avoid 1 in 10 flood) cannot be guaranteed anymore. The frequency and type of learning, whether exogenous or endogenous, with a partial or full resolution of uncertainty also needs to be specified, e.g. once every 30 years exogenously.

Equation 3 presents an example of a cost-effectiveness problem set up as a Bellman equation which is solved recursively (van Der Pol et al. 2015)

$$J_t(\varphi, x) = \min z \left(\frac{I(z)+O(x+z)}{(1+\delta)^t} + E\{J_{t+1}((\varphi_{t+1}|\varphi), x+z)\}\right) \quad (3)$$
$$s.t. R(f, x+z) \geq \alpha$$

where J_t is the value function, x the stock variable of the system element, z the additional investment at each time step, and φ describes distribution of the uncertain parameter today and in the next time period. The cost function depends on the investment cost I, the maintenance cost O and the discount rate δ. Finally, this is subject to a reliability constraint R which depends on x + z and f the distribution of specific rainfall events, and α the predefined reliability standard.

The option value can then be calculated: the incremental amount to spend on the design and construction of the flood mitigation measures compared to the costs of a baseline, inflexible flood mitigation measure. The present value of the total costs of the RO mitigation measure must be less than or equal to the present value of the total costs of the non-flexible mitigation measure (NRO) (if they are not then there is no benefit to the adjustable mitigation measure and a large flood mitigation measure should be installed from the outset). Alternatively, the present value of benefits from the RO must exceed or be equal to the present value of the NRO measure.

2.10.2.3 Water management – application of robust decision-making

In some cases farm-level adaptation in the livestock sector requires integration with a wider set of policies. This may be the case in a region suffering from water scarcity where a holistic water management approach is needed. Water may be needed for irrigation of fields, drinking water for animals, as well as for household use. Meeting the demands of all stakeholders under such conditions can be extremely challenging even without the changes in future water availability resulting from climate change. An adaptation appraisal method that works well in such situations is Robust Decision Making (RDM). The concept of robust decision making is not new (Matalas and Fiering 1977) and has been used in different variations but it is most prominently linked to the RAND Corporation (Lempert et al. 2003). It was originally designed for decision-making in poorly-characterised uncertainty with a subsequent application to climate change adaptation (Lempert et al. 2006).

RDM can help to structure a complex decision making process with a large set of options. It helps to understand the potential consequences of strategies over many scenarios.

In general, RDM models will strongly depend on the adaptation problem analysed. If needed, the analysis can be simplified according to the decision-makers' needs by reducing the range of climate scenarios and other uncertainties considered as well as the number of strategies.

In a first step, the aim of the decision-making process and a number of potential strategies need to be defined. Ideally, the potential strategies must be sufficiently differentiated to allow for a meaningful comparison of trade-offs. For water demand this may be a certain supply to all parties involved over a specific time period and how this might be accomplished for example, through irrigation measures, water conservation devices, reduction of water leaks, local water consumption audits. The second step includes identifying uncertain parameters and their plausible ranges including climate change impacts, future water demand and others. This is a crucial task as it will define the vulnerability of different strategies. Values may be obtained from literature, expert opinion elicitation or stakeholder consultation. The choice and range of these parameters is determined by the decision-maker, introducing unavoidable subjectivity. RDM applied fully quantitatively is very data and resource intensive, but to avoid overly complex outcomes it may be advisable to limit the number of uncertainties. For the uncertainty concerning climate change, simulation models are used to create large ensembles (thousands or millions of runs) of multiple plausible future scenarios from the parameters without assuming a likelihood of the different scenarios. A simplified version will use fewer model runs however at the cost of potentially ignoring the least vulnerable option.

In a third step, costs and benefits of different measures are assessed. This includes hydrological modelling for the area of interest in order to predict changes in flows under different climate change scenarios as well as demand models for agricultural and potentially household water demand. Subsequently, the different strategies are tested against a robustness criterion, which may be that the strategy performs well compared with alternative strategies in many different future scenarios or a certain cost-benefit measure (Lempert and Schlesinger 2000). In an iterative process, the candidate strategies can be adjusted and fed repeatedly through the ensembles. Accordingly, RDM does not predict uncertainty and then rank alternative strategies, but characterizes uncertainty in the context of a specific decision: the most important combinations of uncertainties to the choice among alternative options are determined in different plausible futures. As a result of the analysis trade-off curves compare alternative strategies rather than providing any conclusive and unique ordering of options. Generally, a strategy that performs well over a range of plausible futures might be chosen over a strategy that performs optimally under expected conditions.

2.11 Discussion and conclusion

The second part of Chapter 2 uses the result of the first part of Chapter 2 that the lead-time and lifetime of an adaptation action determines the appropriate method of economic appraisal for decision making. Adaptations that can take effect relatively instantaneously can wait until the climate is observed to have changed, and can be reversed if they are no longer appropriate. They can be appraised through (expected) formal or informal CBA. It is clear that many of the adaptations suggested for agriculture are short term and reversible, and therefore standard appraisal tools such as CBA remain appropriate. Furthermore, CBA is easily applied and its interpretation is familiar and relatively intuitive to most decision makers.

Longer-term adaptation options should be appraised with robust tools under uncertainty. However, this section also acknowledges the caveats of those conclusions reached in the first part of Chapter 2 in an applied context such as the livestock sector. More vulnerable farmers operating at the economic margins, including those in developing countries, may not be able to cope with even one drought or flood, and they may therefore need to think further ahead about their options for increasing resilience. Other farmers may have the ability to 'absorb' the costs of climate change rather than taking adaptive action up to a certain point. Many factors influence farmers' decision-making and the 'threshold' at which they decide to adapt will vary across farms.

It should also be noted that despite the short lead and life-time of many options, farmers will not know the consequences of their actions with certainty in particular where there is increased weather variability under climate change. In such contexts, the use of expected utility theory with the inclusion of risk coefficients and PA can prove useful as a way to guide decision-making.

Most of the decision-making for the adaptations covered in this paper would be made by private individuals (in this context livestock farmers). However some of the options that require robust appraisal techniques may fall under the realm of public decision-making, such as large-scale water storage facilities or flood defence schemes. This analysis is therefore also of critical importance to public decision-makers, who need to make strategic decisions with scarce resources. It should be noted that the adaptations here are incremental rather than transformative, intended to avoid disruptions of the current systems (Kates et al. 2012). In some locations this will not be sufficient due to high risk and vulnerability. Such transformation requires not only acceptable adaptation options but also supportive social and institutional contexts (Kates et al., 2012) and the integration of market risk. In the European livestock sector we may speculate that such options include changing the type of agricultural activity (e. g. from crops to livestock) or even abandoning agriculture as an income source in certain areas on the supply side (Howden et al., 2007). On the demand side, this may include attempts to reduce meat consumption (which also benefits mitigation) (Ripple et al. 2014). The latter point shows that climate change will not necessarily be the main driver of decision-making, other factors such as market risk and policy changes will prove influential.

3 Economic appraisal of afforestation for flood management under climate change and associated ecosystem benefits

Ruth Dittrich, Tom Ball, Anita Wreford, Dominic Moran

Ruth Dittrich is the main author of chapter 3. She conducted the literature research, gathered the data on the cost-benefit analysis from various sources as well as carried out the cost-benefit analysis. She also wrote the description of the methods and the discussion. She calculated as well the change in rainfall return periods under climate change using UKCP09 data.

Tom Ball provided the hydrological analysis which is used as an input to the cost-benefit analysis and wrote the description of the hydrological model.

Anita Wreford and Dominic Moran provided feedback on the structure and content on the drafts of chapter 3.

The aim is to publish chapter 3 in a peer-review journal after some modifications to shorten the chapter.

3.1 Abstract

Increased flood frequency is considered a major risk under climate change and protecting vulnerable communities is a key public policy objective. Natural flood management measures (NFM) are increasingly discussed as a less disruptive and more cost-effective means than hard engineered measures when providing flood regulation, particularly when considering additional ecosystem services beyond flood regulation. This paper provides a cost-benefit analysis over 75 years of the impacts of afforestation as a NFM on peak flows under climate change, and on additional ecosystem services in a rural catchment in Scotland. We model five scenarios, riparian woodland afforestation, 30%, 64% and 100% afforestation of the catchment with broadleaves, as well as a combination of 100 % afforestation and riparian woodland. These scenarios are analysed under climate change scenarios using

UKCP09 weather generator data for the flood regulation impacts. We found significant positive net present values (NPV) for all scenarios considered. However benefits are dominated by ecosystem services co-benefits rather than flood regulation, with values related to climate regulation, aesthetic appeal, recreation and water quality contributing to a high positive NPV. All afforestation scenarios provide some flood regulation benefits, which increase with the degree of afforestation and are greater for higher frequency flood events. The investment in riparian woodland (under low and central climate change scenarios) delivers positive NPV alone when considering only flood regulation benefits. The case study suggests that afforestation as a sole NFM measure provides a positive NPV in some cases but highlights the importance of identifying and quantifying additional ecosystem co-benefits.

3.2 Introduction

Climate change is expected to increase the risk of inland and coastal flooding in Scotland causing severe impacts across multiple sectors of the economy and direct threats to human livelihoods and well-being murphy (Scottish Government 2016). A report for the UK Climate Change Committee (Sayers 2015) estimated that present day expected Average Annual Damages[5] (AAD) in Scotland of £160m will increase by 56% to £241m (under a 2°C climate change projection) and by 140% to £390m (under a 4°C climate change projection) by 2080, assuming no population growth and continued adaptation at current levels. The current most significant source of flooding in the UK is fluvial (river), contributing £560m (40%) of total estimated average damages (Sayers 2015). This is reinforced by evidence from recent climate studies (Herring et al. 2015; Herring et al. 2014; Kay et al. 2011; Pardeep et al. 2011; Peterson et al. 2012) applying probabilistic event attribution that suggest the influence of climate change on some recent flood events may already be detectable and should be anticipated.

Traditional approaches to flood control across Europe have emphasised hard engineering solutions to protect high value infrastructure (European Commission 2011), and to defend agricultural production on drained wetlands and floodplains (Iacob et al. 2014). Landowners have implemented measures to decrease flood risk locally but may thereby have impeded flood control downstream (Newson and Robinson 1983; Robinson and Rycroft 1999). Such schemes often have significant environmental impacts because they disrupt natural flow and storage processes. It is also likely that land use change in catchments, particularly loss of forest cover, riparian zone embankments and channel straightening have amplified current risk and vulnerability to the increased runoff predicted by climate change models (Bronstert et al. 2002; Darby 1999; Stover and Montgomery 2001; Werritty et al. 2010; Werritty et al. 2006).

In contrast, the introduction of natural flood management measures (NFM) potentially provides greater adaptive capacity to negate climate change by re-naturalising flows, or at

[5] The expected average damage per year that would occur in a specific area from flooding over a very long period of time.

least provides a buffer against subsequent flow regime changes (Iacob et al. 2014). NFM involves the utilisation or restoration of 'natural' land cover and channel-floodplain features within catchments to increase the time to peak and reduce the height of the flood wave downstream (Environment Agency 2010). This involves altering multiple elements of a catchment water balance by promoting interception, infiltration and groundwater storage, enhancing water losses through evapotranspiration, lengthening hydrological pathways and increasing flow resistance.

Afforestation is among the natural flood management measures applied in the UK (Forest Research 2016) and elsewhere in Europe (European Commission 2011). Over time trees develop a complex root system (growing and dying) creating preferential pathways for water flow and promoting higher infiltration rates (Archer et al. 2002; Schwärzel et al. 2012). Combined with higher rates of interception and evapotranspiration this results in reduced runoff and sediment production (Calder 1990).

The influence of forests in the form of upstream or riparian woodland on flood flows is investigated either empirically through monitoring of (sub)-catchments or through hydrological modelling assessments (Nisbet et al. 2011). Empirical evidence is still limited given that it takes approximately +10-20 years for the forests to grow fully and to have a role in the hydrological cycle. However these studies demonstrate positive effects of coniferous forests on peak flow reduction for smaller events (Kirby et al. 1991; Price 2000; Robinson 1998; Robinson et al. 2003; Rothacher 1970; Swank 1988). Hydrological modelling studies of both coniferous, broadleaf and riparian woodland also suggest a decrease in flood peak or changes in flood risk probability given different forest covers in the catchment (Bulygina et al. 2009; Calder and Aylward 2006; Francés et al. 2008; Naden 1996; Nisbet and Thomas 2008; Odoni and Lane 2010; Thomas and Nisbet 2007; Wheater et al. 2012; Wheater et al. 2010). The relationship is between afforestation and peak flow reduction is positive at an increasing rate, but the effectiveness diminishes as storm intensity increases. Also, the effects are greater for small catchments (Iacob et al. 2014). Bathurst et al. (2011) consider for a range of rainfall events that forest cover must change by at least 20-30 % to achieve a noticeable alteration in peak discharge for large catchments. A complete (133 ha) and partial (50 ha) of forestation of the floodplain of the River Cary sub-catchment of the River Parret, England would – for a 1 in 100 year event - increase time to flood peak from 180 minutes to 320 and 210 minutes respectively, as well as adding floodplain storage of 71% and 15% respectively

(Thomas and Nisbet 2007). Using reduced complexity hydrological modelling, Dixon et al. (2016) found positive effects on peak magnitude reduction for a 1 in 30 year event on the catchment scale in the Lymington River catchment, in southern UK for forested floodplains (6% reduced through a 10-15% forest cover) but riparian woodland in particular showed promising effects of 19 % peak flow reduction from a 20-40 % forest cover at the sub-catchment scale. Odoni et al. (2010) also showed for a 1 in 100 year event reductions of peak flow of 8-10 % due to 50 ha of riparian woodland (combined with 100 woody debris dams), as well as a 14 % increase in storage from 30 ha of flood plain woodland in the Pickering catchment, England.

The performance of NFM and afforestation in particular will ultimately be dependent on site-specific conditions, including landscape setting, catchment characteristics, the degree of hydromorphological alteration and the extent and appropriateness of the different measures adopted (Iacob et al. 2014). Runoff reductions are likely to be larger and more sustained from re-afforested grassland compared with scrubland (Farley et al. 2005). Also, the spatio-temporal variations in rainfall and runoff have a significant impact on peak flow reduction (Pattison and Lane 2012). It should also be noted that there is no conclusive evidence that local scale impacts on peak flow can be identified at the catchment scale (Environment Agency 2007).

NFM can also offer ecosystem co-benefits in addition to flood regulation benefits, for example recreational, biodiversity and climate regulation (Bateman et al. 2011; EFTEC 2010; Entec and Hanley 1997; Hanley et al. 2002; Willis et al. 2003). Hence the benefit-to-cost ratio (BCR) of any scheme is potentially more favourable when these are considered (Forbes et al. 2015; Iacob et al. 2014). Indeed, for many small communities, hard engineering measures may never be viable due to too low benefit-cost ratios or limited public budgets (ASC 2014), while NFM may provide a valuable contribution to reducing peak flows at a lower cost in particular for smaller-scale flooding problems, and can be partially complemented by household flood protection measures (Scottish Government 2014). With the prospect of increasing flooding impacts from more frequent and extreme weather (ASC 2014; IPCC 2014a), enhancing resilience is crucial (ASC, 2014). It is thus not surprising that NFM is attracting more policy interest across Europe (European Commission 2011; Forest Research 2016) and within the UK, in particular in Scotland. Enshrined in the Flood Risk (Scotland)

Management Act 2009 (Scottish Government 2009a), all statutory bodies are asked to consider the use of NFM approaches where possible.

Despite this growing interest in NFM, economic appraisals of the flood regulation benefits of afforestation measures are rare. One detailed case study for the Pickering Beck catchment in North Yorkshire (UK) demonstrated a range of land management measures including riparian and non-riparian woodland (DEFRA 2011). The study investigated further benefits for ecosystem services of afforestation measures beyond flood regulation, which proved highly positive in particular due to habitat creation and carbon sequestration. The total annual net benefits were estimated to be £203,687. A related study (DEFRA 2013a) evaluated the outcomes under different climate change outcomes, and showed positive net benefits even for the worst case outcomes, thus strengthening the case for NFM.

Given the limited evidence on NFM appraisal this paper aims to provide a better understanding – both in biophysical and economics terms – of afforestation as a NFM measure and its potential role as a climate change adaptation strategy. Chapter 3 therefore provides the continuation of the discussion on appropriate decision-making tools for appraising adaptation options with a case study level that applies a decision-making tool which considers climate change uncertainty in the appraisal process, namely scenario-based cost-benefit analysis. This allows understanding better the strengths and weaknesses of this tool for the appraisal of NFM as an adaptation measure. This chapter specifically demonstrates the effects of different afforestation scenarios on flood regulation and other ecosystem services for a catchment in Scotland for riparian and broadleaf woodland. The different afforestation configurations are tested under alternative climate change scenarios for flood management and combined with the ecosystem services benefits to derive cost and benefit estimates.

The remainder of the paper is structured as follows: Section 3.3 introduces the case study and presents our methodology; subsequently, in section 3.4 we present and discuss our results. Section 3.5 provides a short conclusion.

3.3 Case study area and methodology

The Eddleston Water catchment covers 69 km^2 in the Scottish Borders, the river being a tributary of the River Tweed, flowing 17 km north to south before reaching the main river Tweed in the town of Peebles. Channelisation, land drainage and the creation of flood banks have led to a loss of natural habitats, such as wetlands and woodlands (Harrison 2012). This may have led to faster runoff generated upstream increasing the risk of riverine flooding[6] in the village of Eddleston (940 inhabitants) and further downstream in the town of Peebles which are both situated on the Eddleston Water. Figure 3-1 shows a schematic map of the location of the Eddleston Water catchment within Scotland.

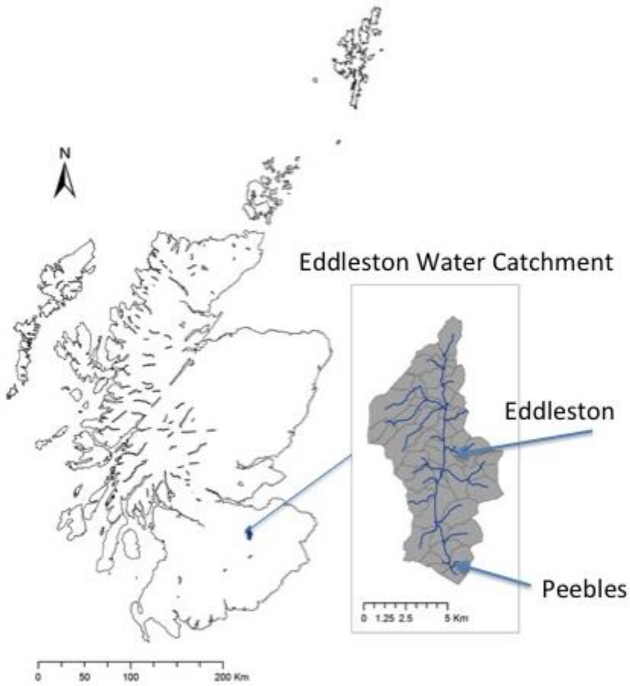

Figure 3-1 Schematic map of the location of the Eddleston Water Catchment within Scotland

A range of natural flood risk management measures have been implemented since 2012 primarily in the upper valley and hill slopes (which are the main sources of flood water running off in to the river). This is the Eddleston Water Project led by the Tweed Forum, an organisation promoting sustainable management in the Tweed Catchment of measures that may have multiple benefits including flood risk reduction. This includes planting of riparian and floodplain woodland, retention ponds, large woody debris flow restrictors and re-meandering of the river and others to decrease flood risk in the areas as well as measures to improve the hydromorphological status of the river under the European Water Framework

6 Riverine floods occur when the river run-off volume exceeds local flow capacities.

Directive (Tweed Forum, 2015). Figure 3-2 shows pictures of different NFM measures. This study focuses on the effects of the current and modelled afforestation on peak flow under different climate change scenarios in Eddleston village as well as impacts on further ecosystem services.

Figure 3-2 Pictures of NFM measures in the Eddleston Water catchment, a) Riparian planting, b) Flow restrictor, c) Re-meandering of Eddleston Water as well as retention pond, d) Re-meandering of Eddleston Water (Pictures provided by the Tweed Forum).

3.3.1 Climate change scenarios

Climate change scenarios were obtained using the UKCP09 weather generator rainfall data for the relevant area. The dataset developed by the Met Office provides historical rainfall data across the UK, which is perturbed based on probabilistic climate change projections. We downloaded 40 sets of 30-year hourly time series with 100 realisations in each set (i.e. in total 1200 realisations) for both the 1990s (the baseline period), the 2040s and the 2080s. We assume the baseline represents 2016 flows, which has been validated against more recent observations from the catchment. The data was analysed with the annual maximum method (Coles 2001) to obtain the rainfall intensity of different return periods for all three periods. The data is conditional on the high, medium and low climate change scenarios. As no information is available on the likelihood associated with the climate change scenarios, we have assumed the medium scenario. However, given the recent evidence on future global emissions (Le Quéré et al. 2015), we must assume that a medium scenario is likely to be a conservative estimate. We grouped the resulting rainfall intensities in percentile bins (25th, 50th and 75th percentile) to explore the lower and higher end climate change outcomes under a medium emission scenario.

3.3.2 Hydrological model and afforestation

The software used for the hydrological model used – HEC-HMS (US Army Corps of Engineers)- is open access and has seen widespread use in catchment management around the world, including for flood risk management (McColl and Aggett 2007; Olang and Fürst 2011; Saghafian et al. 2008; Váňová and Langhammer 2011). The structure simulates the transfer of water from rainfall to runoff through various stores. Meteorological sub-models are used to specify the input rainfall, which can be a monitored dataset, design rainfall inputs, or a combination. Initially, interception and canopy storage intercept a proportion of the rainfall, surface storage then intercepts a further proportion, and the residual rain is available for infiltration to soil, which occurs at a rate that relates to the antecedent conditions for each timestep (15 minutes, the same as the monitoring interval). Evapotranspiration re-transfers some of the moisture to the atmosphere from both soil (non-tension) and canopy, which is a net loss to the system and a component that may be balanced based on known volumes of inflow (rainfall) and outflow (streamflow). Once in the soil, the moisture may percolate down into groundwater stores, again at a specified rate. There is no groundwater flow model capable of modelling the dynamics of spatial transfer in three dimensions (compared with, for example, MIKE-SHE, see above). However, the approach trades-off detailed spatial information with relative simplicity and speed of computation, while preserving an important real-world phenomenon: that of slow transfer of water into and out of soil stores and into deeper groundwater stores.

An aspect of the model that is important to note is that it is deterministic; for a given set of rainfall input and parameter settings, the model will generate the same result. The highly variable and scale-dependent nature of many catchment processes (for example, infiltration) mean that such an approach is an inherent simplification. In particular, it is in the below-ground processes that these aspects are particularly problematic. As an example, the complexity of inflow and outflow of moisture into the various groundwater and soil stores is both scale-dependent and nonlinear. Attribution of any flow changes to land use and associated soil structure changes must bear in mind this simplification of the real world and the attendant uncertainty in predictions that stems from it. However, careful uncertainty analysis was carried out in order to quantify confidence boundaries around the range of model output that factors in the range of possible estimates for several of these parameters.

Changes of flood peak under currently planted riparian woodland (approximately 29 ha), three scenarios of broadleaf afforestation of the catchment (30%, 64% and 100% of afforestation corresponding to 2070 ha, 4416 ha and 6900 ha respectively), as well as a combination of the 100 % afforestation scenario and the riparian woodland were analysed. The trees on the hill slopes lead to modifications in infiltration, canopy storage and percolation and will reduce the amount of water reaching the channel in a given time. Riparian woodlands are related to or situated on the banks of a river, or to wetland adjacent to rivers and streams. They affect the routing, which is the travel of a flood wave moving down a floodplain as well as the frictional roughness of the flood plain. The effects of the riparian woodland on flood regulation are likely to be slightly over-estimated due to the model requiring a minimum area to be specified, which is in some places greater than the actual planted areas.

NFM measures are evolutionary in nature and the lag times in relation to consequent effects on runoff response are debated (Bonell et al. 2010; Hümann et al. 2011; Krishnaswamy et al. 2012). Andréassian (2004) and Farley et al. (2005) note that stream flow response to afforestation is anticipated to be very rapid (within 5 years of planting) with maximum runoff reductions achieved between 15 and 20 years. In our model, we assume that flood regulation benefits are fully realised from year 15 onwards and increase linearly from 15% from year

3.3.3 Flood regulation benefits

The timeframe for the cost-benefit analysis is 75 years based on the climate change projections until 2080. Costs and benefits are in 2012 prices when most riparian woodland was planted and the main cost incurred. In addition to delivering flood alleviation benefits, the riparian woodland was also planted to improve the river status under EU Water Framework Directive (Council Directive 2000/60/EC). Although the flood regulation benefits can also be considered as ecosystem services, due to the focus on flood alleviation in this study, we present the results separately.

The flood regulation benefits (i.e. avoided damage from flooding) were obtained using the multi-coloured handbook (MCH) commonly used in the UK for flood risk assessments (Penning-Rowsell et al. 2010). To calculate the benefits of a flood alleviation scheme, the calculations are carried out with and without the scheme to obtain a comparison: the damage avoided under the scheme equals the benefits.

The baseline river response in Eddleston village was characterised by 2.5 years of pre-intervention flow monitoring using a gauge whose height was related to the LIDAR[7] using a ground survey. For each of the properties at risk we estimated their height using LIDAR data and calculated inundation depth relative to the river level for different flood events. With this information, we obtained depth-damage matrices for the different properties[8], which were added up and from which we obtained AAD for the whole village (Arnell 1990). As the depth-damages matrices have point estimates for different depths (0.05 m, 0.10 m, 0.2 m, 0.3 m, 0.4 m and 0.6 m) any flood depth between these point estimates will fall into either the next lower or higher category. Therefore, even if there is a reduction in peak flow due to the afforestation, the damage cost can remain the same, if the flood depths before and after remain within the same category. We therefore fitted curves through the damage estimates for the different point estimates to obtain a function for the flood damage and more detailed damage results.

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7 Light Detection and Ranging—is a remote sensing method used to examine the surface of the Earth.

8 The calculations employ economic loss (i.e. depreciated value) rather than financial loss (the replacement value) to reflect the loss to society rather than to the household. They exclude VAT which is a transfer within society. Present value damages are capped at the market value of the house price to avoid over-estimation of damages.

3.3.4 Further ecosystem benefits

The UK National Ecosystem Assessment (UK NEA 2011) is built on the global Millennium Ecosystem Assessment (MA 2001), to provide the first systematic assessment of goods and services provided by the natural resources underpinning the UK economy. It provides a framework for the consideration of further ecosystem services for the current study. This assessment The NEA distinguishes between provisioning, regulating, cultural and supporting services. Table 3-1 outlines forest-related services. Supporting services are not included in the analysis to avoid double-counting as they are intermediate services to other final services (Hanley et al., 2002). This includes for example water recycling which supports the water quality benefit.

This study uses a benefit transfer approach for ecosystem valuation, deriving values from previous studies. There are numerous valuation estimates for woodlands and values are sometimes difficult to compare and standardise to common units (Bockstael et al. 2000). First, the ecosystem service impacts of forestry depend heavily on the species, spacing and mix of trees grown, the types of habitat they replace, and their context/ location in the landscape (EFTEC 2010). To address this we chose studies from the UK with a similar context (Brainard et al. 2003; EFTEC 2010; Hanley et al. 2002; Ray 2008; Willis et al. 2003). Second, any ecosystem service may exhibit a non-linear marginal value function. The marginal recreational values of a tiny woodland may be trivial and can initially increase with size, but eventually exhibit declining marginal values (Bateman et al. 2011). At the same time, the marginal value of loss of the disappearing current land-use will increase (Bockstael et al. 2000). We attempt to reflect those potentially decreasing marginal values by choosing very low values in those categories to avoid over-estimation of those benefits. Additionally, the analysed areas are sufficiently small for constant marginal values to be a reasonable approximation. Third, ecosystem services are likely to change with climate change (Pedrono et al. 2016). We include these changes specifically for flood regulation, however it was beyond the scope of the study to investigate the changes on further co-benefits.

Table 3-1 summarises ecosystem services that are impacted by afforestation with the minus and plus symbols indicating a (strong) negative or (strong) positive influence. We differentiate between the impacts of the currently planted riparian woodland and the modelled broadleaves, as their effects vary to an extent. It was not feasible to obtain monetary estimates for all listed ecosystem services, which is partly due to their limited impact as well as lack of data. The monetised ecosystem services are marked with an asterisk.

	Riparian woodland	Broadleaf woodland
Provisioning		
Food (wild food)	0	0
Renewable energy (fuel woods)	0	0
Timber (Furniture)	0	0
Regulatory		
Air quality	+	+
Climate change regulation*	+	+
Water supply	0	0
Flood regulation*	++	++
Erosion	++	+
Water quality*	++	0
Cultural		
Recreation*	+	+
Aesthetic	++	+
Education*	++	++
Biodiversity*	++	+
Supporting		
Soil formation	+	+
Photosynthesis	0	+
Nutrient cycle	++	+
Water recycling	+	0

Table 3-1 Direction of impact on ecosystem services of riparian woodland and of broadleaves.

3.3.5 Provisioning services

The riparian broadleaf woodland was exclusively planted for NFM and WFD purposes, thus no timber will be harvested. The same applies for the modelled broadleaf woodland, which would be managed only for NFM objectives.

Expansion in forest cover can impact water supply by increasing the interception of rainfall and decreasing runoff volume (Brander et al. 2009; Calder 1999; Stednick 1996; Willis 2002). This may negatively affect water supply, in particular under climate change. Willis (2002) noted that British water companies perceive little impact of existing forestry on water supply costs, however the 2012 UK Climate Change Risk assessment (Rance et al. 2012) notes that water availability is one of the biggest issues facing the water sector . A negative effect on water supply appears unlikely in the current case study due to sufficient water supplied through a range of upland reservoirs (City of Edinburgh Council 2012), combined with private boreholes. Accordingly this is excluded from the calculations, though this may change under climate change.

3.3.6 Regulating services

The climate benefit corresponds to the value of the carbon sequestered by the broadleaf woodland. The total number of hectares of all woodland was multiplied by per hectare carbon sequestration rates in tons (adjusted over time for factors such as fencing, thinning, tree spacing, harvesting, soil preparation for planting, open space and expected growth rate of the woodland in line with the Woodland Carbon Code. The voluntary code has been developed by the Forestry Commission as a guidance to calculate carbon sequestration rates[9]), and with the relevant carbon prices. Note that we do not consider changes to carbon sequestration rates under climate change for which studies have shown mixed results (Achterman et al. 2006; Dai et al. 2012; Dymond et al. 2015; Tian et al. 2016). We use the guidance set out in UK Department of Energy and Climate (DECC 2009) based on estimates of abatement costs towards a global temperature increase limited to 2°C, which is generally applied for policy appraisal in the UK. The relevant prices for the forestry sector are 'non-traded' and rise from £50/tCO_2e in 2008 to £70/tCO_2e in 2030, then to £200/tCO_2e by 2050. We allow for uncertainty in the amount of carbon sequestered by applying the low and high values for the social cost of carbon.

Air quality can be improved through woodlands both via direct absorption of pollutants and through their role in producing oxygen. Air pollution absorption (health effect) of woodland appears to be relatively insignificant in the case study area because of the absence of

[9] http://www.forestry.gov.uk/forestry/infd-88g2ca

significant population numbers and little pollution. This is also because research (Powe 2002) so far has focused on the effects of pollution absorption within 1 km^2 areas. We therefore did not quantify air quality effects.

Riparian woodland can impact water quality positively in a number of ways. First, it may lower the water temperature of the adjacent water course through appropriate shading (Evans 2004; Weatherley and Ormerod 1990). This may have a positive influence on fish, stocks by increasingly dissolved oxygen levels in the water and lowering the metabolism of fish reducing their oxygen use (Lenane 2012; Vardakoulias and Arnold 2015) however there is no relevant data available for the case study area to support this. It is known though, that the juvenile stock of salmon and trout in the case study area was already high before the planting (Tweed Foundation 2009), which makes a significant positive change less likely. Nevertheless, benefits of shading may increase in future under climate change when the number of hot days per year may increase (Murphy et al. 2009).

Second, riparian woodland can significantly reduce the amount of sediment washed into the river. While some sediment is necessary to replenish in-stream habitat, too much can reduce channel flood capacity and disrupt breeding grounds for fish leading to biological degradation (Bettess et al. 2011). Reduced sedimentation lowers the need for potentially costly downstream dredging.

Finally, riparian woodland will likely reduce diffuse pollution from fertilisers (phosphates and nitrates) on adjacent fields by means of their root system thus supporting the nutrient cycle (Leveque 2003). Quantifying these benefits related to water quality is challenging, as there are few relevant studies in the UK (Broadmeadow and Nisbet 2004; Collins et al. 2010), and there is also the risk of double-counting as sedimentation and diffuse pollution effects are supporting services. Instead, we apply the estimates obtained by Metcalfe et al. (2012) on willingness-to-pay (WTP) of households for non-market benefits per km^2 under the WFD in England and Wales to the riparian woodland. The riparian woodland in the catchment was also planted as Eddleston Water with the aim of improving the status from 'bad' to 'good'.

Thus, the estimates can be considered as a proxy for the combined benefits to water quality from riparian woodland and the supporting services described above. We apply their water body valuation function, which takes into account the surface of the water body and population numbers within a 32 kilometres radius. The values in this study represent total WTP for 80 km^2 of water area for the effect of riparian woodland (which corresponds to 36% of all implemented water quality improving measures), relative to a low quality base, for each year at which the water body is at medium quality. While the aim is to ultimately reach good status, it is currently not clear whether this is feasible due to landowners having to agree to further measures. The modelled broadleaves are assumed not to influence the estimate as their planting would not lead to a change in status under the WFD.

Woodland may also reduce erosion and thus improve soil fertility by restricting the amount of fertile soil washed out in woodland areas and by stabilising river banks (Broadmeadow and Nisbet 2004; DEFRA 2011; Laubel et al. 2003). We do not calculate erosion benefits explicitly to avoid double counting, as the benefits are to an extent linked to flood regulation, in particular the stabilisation of river banks, and as there will be little benefits to erosion to adjacent fields as the land use is improved pasture rather than arable land.

3.3.7 Cultural services

Use values in the cultural component include recreation, aesthetic appeal and education, while important non-use values include heritage and biodiversity conservation (EFTEC 2010). Non-use value is the value people assign to goods without (ever) using them (Edwards-Jones, 2000). It is challenging to separate use and non-use values as neither people nor survey instruments may be able to distinguish clearly between values for viewing and experiencing a landscape in a particular configuration or quality, and non-use values associated with the same features. This raises the issue of double-counting. We thus use separate values for recreation, aesthetic and educational values, and consider any additional non-use values under the heading biodiversity, rather than attempting to include a separate value for the former.

Recreational value of forests depends on characteristics of the forest and recreational opportunities within it, travel time and associated costs as well as the availability of substitute sites in the area, and the income and taste characteristics of the population in the area surrounding the forest (Sen et al. 2010; Willis et al. 2003). We do not estimate a recreational benefit for all riparian woodland; 26 ha have been judged as accessible and likely to be used for walking by the Tweed Foundation. The calculation is based on travel cost (the cost of time and travel to the woodland expresses WTP) which have been turned into per hectare values by eftec (2010). We apply the category rural wood with low (£186.12 ha/year) and high values (£2481.6 ha/year) and their central value which is represented by the mean of the two values (£1333.86 ha/year) to reflect uncertainty.

Woods and forests are often considered attractive landscape features, though some forest types can also be thought to detract from natural beauty. Some element of aesthetic value is captured within forest recreational values, but the value of viewing a forest from the outside, for example when driving past, is additional. Values accruing to residents with such views can be estimated using hedonic method (Edwards-Jones et al. 2000). We use the values developed by Entec and Hanley (1997) and adapted by eftec (2010), which suggest £41.36/ha/yr for rural woodlands. We add upper and lower bounds (+/-20 %) for sensitivity analysis. By applying per hectare values, we cannot take into consideration that often only the edges of the woods are visible from homes and transport routes.

The Eddleston Water Project has created opportunities for educational visits of school and student groups and professionals interested in restoration projects and NFM. We use a 'cost of investment' approach to calculate the benefits, which estimates the outlay for making the trip as a proxy of its worth; in this case based on travel cost, i.e. fares and travel time of the students (based on the yearly cost of schooling), relative to the cost of providing knowledge in a normal classroom environment (Mourato et al. 2010). UK NEA (Bateman et al. 2011) estimates the costs to be £16 to £26 per pupil visit for outdoor learning visits. We assume that the number of visits of currently 15 groups each year with approximately 20 people per group will decrease over time as more projects may evolve and curricula change. The last visits are calculated to occur in 2026. We assume that no additional visits occur when the afforested area is expanded, i.e. the educational benefit accrues only to the riparian woodland.

Finally, woodland has positive effects on biodiversity. A broadleaf forest will provide habitat for a number of species (Hanley et al. 2002) and there is strong evidence that riparian woodland is particularly important for landscape biodiversity. Woodlands host species that are rare elsewhere and they support landscape connectivity and may thus act as reservoirs for generalist species (Gundersen et al. 2010). The total value of biodiversity in forests comprises both use and non-use values. Use values are measured through recreational and aesthetic values (e.g. seeing deer while walking or driving past a forest). Non-use values are existence value (the benefit people receive from just knowing that wildlife exists even though they never see it) and bequest value (the benefit people derive from knowing that wildlife will be protected and preserved for the benefit of future generations) (Hanley et al. 2002).

There is limited data as to which woodland types provide what kind of biodiversity, and few studies on the economic valuation of the non-use values of biodiversity. Based on the work of Hanley et al. (2002) on WTP for non-use biodiversity values for different types of woodland, eftec (2010) estimate that the range of non-use values of woodland biodiversity is from £30-£300/ha/yr, depending on the priority status of the woodland. Riparian woodland is considered a high priority, coniferous woodland is low priority woodland and we assume that broadleaves would have medium priority. For the value of riparian woodland, we therefore use low (£180/ha/yr), central (£240/ha/yr) and high (£300/ha/yr) estimates, with the high boundary of the eftec estimate being our high estimate and the central and low values at 20 % less each. For the value of the broadleaves, we use £135/ha/yr as the central value (the central value of the eftec range and +/- 20 % as lower (£108/ha/yr) and upper boundary (£162/ha/yr). We multiply the estimates with the hectare planted/modelled assuming that the biodiversity values increase linearly and reach a constant value either once trees reach the age of 55 (low estimate), 20 (central estimate), or 10 years (high estimate). As for recreation, biodiversity likely exhibits decreasing marginal values per hectare, which are not considered in the calculation (Hanley et al. 2002). It is also possible that the changes in flood return periods may affect the habitat and impacts of climate change on biodiversity (Thompson et al. 2009) which are not considered here.

3.3.8 Cost of afforestation measures

The costs for implementing the afforestation measures can be divided into investment and maintenance costs. Investment costs comprise fixed costs (which accrue independent of the scale of the measure) and variable costs (which increase with the scale of the measure). Maintenance is primarily for machinery to remove dead trees, calculated at £282/ha every five years based on the payments farmers receive for this work through subsidies. Investment costs include planting costs and putting fences in place as well as labour cost. Based on actual estimates, we assume that labour cost equals 75% of a full time position for the first eight years starting in 2012 to include the planning and implementation process and then reduces to 50% and 25% for five years respectively and down to 10 % for the remaining years. For the broadleaf scenarios, we make the assumption that the smaller scenario requires 75 % of the work force and for the two bigger areas, we assume a full-time position. These figures do not change over time due to the much larger areas. For the riparian woodland, we have actual planting estimates for most areas and we use the lowest and highest per hectare values as lower (£1,811/ha) and upper (£2720/ha) boundaries and determine central values as the mean of the boundaries. Fixed costs constitute various fees, which are based on actual figures for the riparian woodland (low, central and high values are respectively, £1,504, £1,712, £1,920). We apply the same estimates to the broadleaf scenarios assuming the costs to be of a similar scale.

Beyond the implementation cost, we need to consider the opportunity cost of agricultural land related to forgone use of land for sheep grazing, which is and was the land use of the (modelled) afforested areas. QMS (2014) figures on sheep profitability for 2012/2013,suggest a net margin of £26 per ewe for improved pasture. We further assume that 1.5 ewes can be fed on one hectare in the case study area (Scottish Government 2015).

3.4 Results

We first present the results of the hydrological analysis for different climate change scenarios with and without the afforestation measures in place. We subsequently show the results of the cost-benefit analysis of the different afforestation measures under different climate change scenarios.

3.4.1 Hydrological analysis

The results of the hydrological analysis highlight that the peak flows of return periods of floods will increase noticeably over time even when considering the conservative 25th percentile scenario. Table 3-2 shows the changes in peak flow for the different forest scenarios, for different percentiles, 2016, 2040 and 2080. Generally, we find a higher relative reduction of peak flow for a 1/20 year event than for a 1/100 year event, confirming what other studies have found, that afforestation is more effective as a flood management measure for smaller events (Iacob et al. 2014). Note that the reduced effect for the 1/100 year event is less pronounced for the riparian woodland, which suggests that floodplain afforestation slows flow on average more effectively than upstream afforestation. We observe a substantial effect when 100 % afforestation is combined with the riparian woodland, for the 1/20 year event, this amounts to 43 % peak flow reduction in 2016 and to 41 % reduction for the 2040 and 2080 scenarios. For the 1/100 year event, the effect is still significant, namely 31 %, 27% and 26% for the three different climate scenarios.

	Baseline			Riparian woodland			Broadleaf afforestation									100 % broadleaf afforestation and riparian woodland		
							30%			64%			100%					
	Percentile			Percentile			Percentile			Percentile			Percentile			Percentile		
	25th	50th	75th	25th	50th	75th	25th	50th	75th	25th	50th	75th	25th	50th	75th	25th	50th	75th
1 in 20 year rainfall event																		
2016																		
Peak flow ($m^3 s^{-1}$)	33.0	33.8	34.7	29.4	30.2	31.3	26.8	27.6	28.5	24.5	25.2	26.0	22.7	23.5	24.4	18.9	19.3	19.9
% flow reduction				11	11	10	19	18	18	26	26	25	31	30	30	43	43	43
2040																		
Peak flow ($m^3 s^{-1}$)	35.9	39.7	42.9	32.8	37.0	40.1	29.5	33.6	36.9	26.6	30.0	33.1	25.2	29.0	32.3	20.1	22.4	25.3
% flow reduction				9	7	6	18	15	14	26	24	23	30	27	25	44	44	41
2080																		
Peak flow ($m^3 s^{-1}$)	37.6	41.9	45.3	34.8	39.1	42.6	31.4	35.9	39.5	28.0	32.1	35.5	26.9	31.3	34.9	21.0	24.3	27.7
% flow reduction				8	7	6	16	14	13	25	23	22	28	25	23	44	42	39

Table 3-2 Peak flow of a 1 in 20 and 1 in 100 year event in Eddleston Village and associated % reduction in peak flow for the following scenarios: riparian woodland, 30%, 64% and 100% broadleaf afforestation, as well as 100% broadleaf afforestation and riparian woodland, for 2016, 2040, 2080, for the 25th, 50th and 75th percentiles of the distribution.

	Baseline			Riparian woodland			Afforestation									100 % afforestation and riparian woodland		
							30%			64%			100%					
	Percentile			Percentile			Percentile			Percentile			Percentile			Percentile		
	25th	50th	75th	25th	50th	75th	25th	50th	75th	25th	50th	75th	25th	50th	75th	25th	50th	75th
1 in 100 year rainfall event																		
2016																		
Peak flow ($m^3 s^{-1}$)	51.7	53.4	55.5	48.5	50.2	52.3	45.8	47.5	49.7	45.3	47.0	49.2	41.3	43.0	45.1	34.9	36.6	38.7
% flow reduction				**6**	**6**	**6**	**12**	**11**	**11**	**12**	**12**	**11**	**20**	**19**	**19**	**32**	**31**	**30**
2040																		
Peak flow ($m^3 s^{-1}$)	56.9	62.2	67.5	54.0	59.4	64.4	51.2	56.8	61.9	50.7	56.3	61.4	46.7	52.2	57.2	40.2	45.8	50.6
% flow reduction				**5**	**5**	**5**	**10**	**9**	**8**	**11**	**10**	**9**	**18**	**16**	**15**	**29**	**26**	**25**
2080																		
Peak flow ($m^3 s^{-1}$)	60.6	65.7	70.1	57.5	62.4	67.0	55.1	60.0	64.6	54.5	59.5	64.0	50.4	55.4	60.0	43.7	48.5	53.5
% flow reduction				**5**	**5**	**4**	**9**	**9**	**8**	**10**	**9**	**9**	**17**	**16**	**14**	**28**	**26**	**24**

Table 3-2 continued

3.4.2 Flood regulation benefits

Table 3-3 presents the effects of the afforestation scenarios for flood regulation based on damages caused by different levels of peak flows. The estimates relate the results of the hydrological analysis presented in Table 3-2 on peak flow reduction to the corresponding decrease in damage cost. The damages for the baseline (i.e. without riparian woodland or broadleaf woodland) and the avoided damages (i.e. the benefits) under the three afforestation scenarios are presented for a 1/20, 1/100 year event and AAD in 2016, for 2040 and 2080. Every afforestation scenario leads to the prevention of damage of a 1/20 RP for all baseline scenarios (for the riparian woodland, this is only true for the 25th and 50th percentile), which equals a median value of £585 000 worth of benefits (if the event occurs) and therefore implicitly also avoids any higher return period than 1 in 20 (such as a 1 in 5 years event). However note that we cannot observe this effect for the 1/20 year event in 2040 and 2080 for riparian woodland. For a 1/100 year event, the riparian woodland leads to a reduction of damages of 5 % under the median scenario. Combining riparian woodland and 100 % afforestation lowers peak flow substantially and no flooding occurs for any climate change scenario for a 1/20 year event.

For the 1 in 100 year event, for 30 % and 64 % afforestation, we observe similar effects even across climate change scenarios (over time), a 6 % to 11 % reduction. Under 100 % afforestation, we observe a median damage reduction of 18 % in 2016 but only a median effect of 12 % for the 2080 scenario. This is even more pronounced for the combination of riparian woodland and 100 % afforestation where the effects decreases from a median damage reduction of 39 % in 2016 to 25 % in 2080.

The third window in Table 3-3 depicts the annual average damage (AAD), which considers the probability of occurrence of the two analysed events with analogous results: more pronounced effects of flood reduction under (lower) 2016 flows for all afforestation scenarios.

The changes of rainfall under climate change have important implications for flood regulation through the afforestation measures, in particular for the 1/20 year event. The current median damage cost of a 1/20 event equals £585 000, which increases by 37% in 2040 and by 38 % in 2080 relative to 2016 (Table 3-3). The increase for the 1/100 year event is less pronounced (an increase of 10% and 14% for 2040 and 2080 relative to 2016). It seems that once a certain flood depth is reached, the additional cost appears to increase at a decreasing rate. Thus, it seems that medium frequency flood events (such as a 1/20 year event) will become more severe in the case study area in the future. While the currently implemented riparian woodland seems to be sufficient in preventing flooding from a 1/20 year event at least under the flow of the 25th and 50th percentile, this is not the case under any climate change scenario for 2040 or 2080. For instance, if the objective was to maintain a flood protection standard of a 1 in 20 year event in the future, further afforestation measures would need to be implemented. It should be noted that the model does not consider further NFM measures such as ponds and log jams which have been implemented throughout the catchment and may have beneficial impacts on peak flow reduction

		Baseline			Riparian woodland		
		Percentile			Percentile		
		25th	50th	75th	25th	50th	75th
	1 in 20 years return period						
2016	Damages (in £ thousands)	486	585	608	-	-	335
	Benefits (in £ thousands)				486	585	273
	% damage avoided				100	100	45
2040	Damages (in £ thousands)	633	802	874	480	664	811
	Benefits (in £ thousands)				153	138	63
	% damage avoided				24	17	7
2080	Damages (in £ thousands)	671	809	891	380	635	766
	Benefits (in £ thousands)				67	86	47
	% damage avoided				10	10	5
	1 in 100 years return period						
2016	Damages (in £ thousands)	1042	1067	1096	985	1014	1052
	Benefits (in £ thousands)				58	1.014	44
	% damage avoided				6	5	4
2040	Damages (in £ thousands)	1114	1183	1246	1076	1148	1209
	Benefits (in £ thousands)				39	35	38
	% damage avoided				3	3	3
2080	Damages (in £ thousands)	1162	1224	1276	1076	1148	1244
	Benefits (in £ thousands)				86	76	32
	% damage avoided				8	7	3

Table 3-3 Damage costs, benefits in £ thousand (2012 prices), % changes relative to baseline for 2040 and 2080 (25th, 50th and 75th percentiles) for the scenarios, riparian woodland, 30%, 64% and 100 % broadleaf afforestation, and 100 % broadleaf afforestation and riparian woodland for a 1/20 and 1/100 year event as well as AAD.

		Broadleaf afforestation					
		30%			64%		
		Percentile			Percentile		
		25th	50th	75th	25th	50th	75th
	1 in 20 years return period						
2016	Damages (in £ thousands)	-	-	-	-	-	-
	Benefits (in £ thousands)	486	585	608	486	585	608
	% damage avoided	100	100	100	100	100	100
2040	Damages (in £ thousands)	325	589	649	-	358	493
	Benefits (in £ thousands)	309	213	224	633	444	381
	% damage avoided	49	27	26	100	55	44
2080	Damages (in £ thousands)	-	467	620	-	380	605
	Benefits (in £ thousands)	291	218	158	671	386	304
	% damage avoided	43	26	17	100	45	33
	1 in 100 years return period						
2016	Damages (in £ thousands)	940	970	1.014	924	955	999
	Benefits (in £ thousands)	103	98	82	118	955	96
	% damage avoided	10	9	7	11	11	9
2040	Damages (in £ thousands)	1028	1110	1175	1028	1110	1175
	Benefits (in £ thousands)	86	73	72	86	73	72
	% damage avoided	8	6	6	8	6	6
2080	Damages (in £ thousands)	1097	1162	1211	1084	1149	1211
	Benefits (in £ thousands)	65	62	65	78	75	65
	% damage avoided	6	6	6	8	7	6

Table 3-3 continued

		Broadleaf afforestation 100%			100 % broadleaf afforestation + riparian woodland		
		Percentile			Percentile		
		25th	50th	75th	25th	50th	75th
	1 in 20 years return period						
2016	Damages (in £ thousands)	-	-	-	-	-	-
	Benefits (in £ thousands)	486	585	608	486	585	608
	% damage avoided	100	100	100	100	100	100
2040	Damages (in £ thousands)	-	-	467	-	-	-
	Benefits (in £ thousands)	633	802	407	633	802	874
	% damage avoided	100	100	47	100	100	100
2080	Damages (in £ thousands)	-	-	-	-	-	-
	Benefits (in £ thousands)	671	472	320	671	852	924
	% damage avoided	100	55	35	100	100	100
	1 in 100 years return period						
2016	Damages (in £ thousands)	844	877	924	612	649	693
	Benefits (in £ thousands)	198	191	172	430	418	403
	% damage avoided	19	18	16	41	39	37
2040	Damages (in £ thousands)	955	1056	1124	814	933	1022
	Benefits (in £ thousands)	160	127	123	387	349	332
	% damage avoided	14	11	10	35	29	27
2080	Damages (in £ thousands)	1014	1097	1149	814	933	1022
	Benefits (in £ thousands)	148	127	126	348	291	253
	% damage avoided	14	12	11	30	24	20

Table 3-3 continued

		Baseline			Riparian woodland		
			Percentile			Percentile	
		25th	50th	75th	25th	50th	75th
	Annual average damages						
2016	Damages (in £ thousands)	31	33	34	20	20	28
	Benefits (in £ thousands)				11	13	6
	% damage avoided				36	39	19
2040	Damages (in £ thousands)	35	40	42	31	36	40
	Benefits (in £ thousands)				4	3	2
	% damage avoided				11	9	5
2080	Damages (in £ thousands)	37	42	44	34	38	37
	Benefits (in £ thousands)				3	3	7
	% damage avoided				8	8	16

Table 3-3 continued

		Broadleaf afforestation					
		30%			64%		
		Percentile			Percentile		
		25th	50th	75th	25th	50th	75th
	Annual average damages						
2016	Damages (in £ thousands)	19	19	20	18	19	20
	Benefits (in £ thousands)	12	14	14	12	14	14
	% damage avoided	39	41	40	40	42	41
2040	Damages (in £ thousands)	27	34	36	21	0	33
	Benefits (in £ thousands)	8	6	6	14	29	9
	% damage avoided	23	14	14	41	26	21
2080	Damages (in £ thousands)	30	36	40	22	32	37
	Benefits (in £ thousands)	7	6	4	15	9	7
	% damage avoided	19	13	10	41	22	17

Table 3-3 continued

		Afforestation 100%			100 % afforestation + riparian woodland		
		Percentile			Percentile		
		25th	50th	75th	25th	50th	75th
	Annual average damages						
2016	Damages (in £ thousands)	17	18	18	12	13	14
	Benefits (in £ thousands)	14	16	16	18	20	20
	% damage avoided	45	47	46	60	61	59
2040	Damages (in £ thousands)	19	21	32	16	19	20
	Benefits (in £ thousands)	16	19	11	19	21	22
	% damage avoided	45	47	25	53	53	52
2080	Damages (in £ thousands)	20	30	35	16	19	20
	Benefits (in £ thousands)	16	12	9	20	23	24
	% damage avoided	45	29	20	56	55	54

Table 3-3 continued

3.4.3 Overall results

Table 3-4 presents the net present values (NPV) (i.e. discounted benefits – costs) for all scenarios per year. The 25th, 50th and 75th percentiles of the flood regulation analysis were matched with the low, central and high scenarios respectively of the further eco-system services analysis. Some of the values are 0 in the table as a result of low figures being expressed in thousands and rounded and thus hardly impacting the overall result.

All scenarios in Table 3-4 show a positive NPV indicating that all investments would be worthwhile ranging from £81,000 per year (central scenario) for the riparian woodland only, to £1,95 million per year (central scenario) for 100 % afforestation combined with riparian woodland. Overall the highest total NPV is observed for the combination of 100 % afforestation and riparian woodland, however the highest benefit-cost ratio can be observed for the riparian woodland with the central estimate being 14.1, whereas the central estimate for 100 % afforestation and riparian woodland is 7. This shows that the benefits relative to the costs are greater for the riparian woodland (i.e. 14.1 fold).

The NPVs across climate change scenarios are very similar as flood regulation is the only element that changes with the climate change scenarios but constitutes at the same time a very low percentage of the overall benefits (around 1 % across the scenarios). The riparian woodland that was implemented in the catchment is the only scenario under which the flood regulation benefits make the investment worthwhile given the cost under the low and central scenario (i.e. 25th and 50th percentile): the yearly cost of the central riparian scenario equals £6,000 and the yearly flood regulation benefit adds up to £13,000. This confirms the results of other studies which indicate the potentially strong impact of riparian buffers on flood risk (Dixon et al. 2016).

For all other scenarios the NPV becomes negative when only considering flood regulation and generally the greater the level of afforestation, the greater the loss. The flood regulation benefits for all scenarios would likely increase if the damage reduction for the town Peebles further downstream were considered.

With respect to eco-system services (excluding flood regulation), the values for the different scenarios show a great disparity which reflects the uncertainty of the underlying data for ecosystem services. For example, the low and high NPV (excluding flood regulation) for the 30 % afforestation scenario are £267,000 and £867,000 respectively and the low and high NPV for the 100 % afforestation scenario amount to £900,000 and £ 2.9 million per year. For the broadleaf scenarios the net benefits increase considerably with the amount of afforestation as the costs do not increase proportionately with the benefits.

	2016			2040			2080		
	Low (£ thousands per year)	**Central** (£ thousands per year)	**High** (£ thousands per year)	**Low** (£ thousands per year)	**Central** (£ thousands per year)	**High** (£ thousands per year)	**Low** (£ thousands per year)	**Central** (£ thousands per year)	**High** (£ thousands per year)
BENEFITS									
RIPARIAN WOODLAND									
Flood regulation benefits	11	13	6	4	3	2	3	3	7
Climate regulation	2	4	7	2	4	7	2	2	2
Recreation	1	5	9	1	5	9	1	5	9
Water Quality	40	71	103	40	71	103	40	71	103
Aesthetic Value	0	1	1	0	1	1	0	1	1
Education	0	1	1	0	1	1	0	1	1
Biodiversity	1	2	3	1	2	3	1	2	3
BROADLEAF WOODLAND									
30%									
Flood regulation benefits	12	14	14	8	6	6	7	6	4
Climate regulation	303	618	935	303	618	935	303	618	935
Recreation	1	4	3	1	4	3	1	4	3
Water Quality	-	-	-	-	-	-	-	-	-
Aesthetic Value	26	32	39	26	32	39	26	32	39
Education	-	-	-	-	-	-	-	-	-
Biodiversity	2	5	13	2	5	13	2	5	13

Table 3-4 Benefits, costs, net present value, and benefit-cost-ratio of the afforestation scenarios, riparian woodland, 30%, 64%, 100% broadleaf afforestation as well as 100 % afforestation and riparian woodland for 2016, 2040, 2080 for low, central and high scenarios.

	2016			2040			2080		
	Low (£ thousands per year)	**Central** (£ thousands per year)	**High** (£ thousands per year)	**Low** (£ thousands per year)	**Central** (£ thousands per year)	**High** (£ thousands per year)	**Low** (£ thousands per year)	**Central** (£ thousands per year)	**High** (£ thousands per year)
BENEFITS									
64%									
Flood regulation benefits	12	14	14	14	10	9	15	9	7
Climate regulation	646	1317	1994	646	1317	1994	646	1317	1994
Recreation	2	3	4	2	3	4	2	3	4
Water Quality	-	-	-	-	-	-	-	-	-
Aesthetic Value	55	67	80	55	67	80	55	67	80
Education	-	-	-	-	-	-	-	-	-
Biodiversity	3	12	28	3	12	28	3	12	28
100%									
Flood regulation benefits	14	16	16	16	19	11	16	12	9
Climate regulation	1010	2059	3117	1010	2059	3117	1010	2059	3117
Recreation	3	4	9	3	4	9	3	4	9
Water Quality	-	-	-	-	-	-	-	-	-
Aesthetic Value	87	108	130	87	108	130	87	108	130
Education	-	-	-	-	-	-	-	-	-
Biodiversity	5	18	43	5	18	43	5	18	43

Table 3-4 continued

	2016			2040			2080		
	Low (£ thousands per year)	**Central** (£ thousands per year)	**High** (£ thousands per year)	**Low** (£ thousands per year)	**Central** (£ thousands per year)	**High** (£ thousands per year)	**Low** (£ thousands per year)	**Central** (£ thousands per year)	**High** (£ thousands per year)
BENEFITS									
100 % BROADLEAF WOODLAND + RIPARIAN WOODLAND									
Flood regulation benefits	18	20	20	19	21	22	20	23	24
Climate regulation	1013	2063	3124	1013	2063	3124	1013	2061	3119
Recreation	3	9	18	3	9	18	3	9	18
Water Quality	40	71	103	40	71	103	40	71	103
Aesthetic Value	87	109	131	87	109	131	87	109	131
Education	0	1	1	0	1	1	0	1	1
Biodiversity	6	20	46	6	20	46	6	20	46
TOTAL BENEFITS									
Riparian woodland	56	96	129	49	87	125	48	85	125
Broadleaf woodland									
30%	343	673	1.004	339	666	996	339	665	995
64%	719	1413	2121	721	1409	2116	722	1408	2114
100%	1118	2205	3315	1121	2208	3310	1121	2201	3308
100 % broadleaf woodland + riparian woodland	1168	2293	3443	1168	2294	3444	1170	2294	3441

Table 3-4 continued

	2016			2040			2080		
	Low (£ thousands per year)	**Central** (£ thousands per year)	**High** (£ thousands per year)	**Low** (£ thousands per year)	**Central** (£ thousands per year)	**High** (£ thousands per year)	**Low** (£ thousands per year)	**Central** (£ thousands per year)	**High** (£ thousands per year)
COSTS									
RIPARIAN WOODLAND									
Planning costs	0	0	0	0	0	0	0	0	0
Planting costs	1	2	2	1	2	2	1	2	2
Opportunity cost	0	0	1	0	0	1	0	0	1
Maintenance cost	3	4	5	3	4	5	3	4	5
BROADLEAF WOODLAND									
30%									
Planning costs	0	0	0	0	0	0	0	0	0
Planting costs	1	2	2	1	2	2	1	2	2
Opportunity cost	24	30	35	24	30	35	24	30	35
Maintenance cost	39	49	85	39	49	85	39	49	85
64%									
Planning costs	0	0	0	0	0	0	0	0	0
Planting costs	2	2	2	2	2	2	2	2	2
Opportunity cost	52	65	78	52	65	78	52	65	78
Maintenance cost	79	99	118	79	99	118	79	99	118

Table 3-4 continued

	2016			2040			2080		
	Low (£ thousands per year)	**Central** (£ thousands per year)	**High** (£ thousands per year)	**Low** (£ thousands per year)	**Central** (£ thousands per year)	**High** (£ thousands per year)	**Low** (£ thousands per year)	**Central** (£ thousands per year)	**High** (£ thousands per year)
COSTS									
100%									
Planning costs	0	0	0	0	0	0	0	0	0
Planting costs	2	2	3	2	2	3	2	2	3
Opportunity cost	81	101	122	81	101	122	81	101	122
Maintenance cost	119	218	262	119	218	262	119	218	262
100 % BROADLEAF WOODLAND + RIPARIAN WOODLAND									
Planning costs	0	0	0	0	0	0	0	0	0
Planting costs	3	4	5	3	4	5	3	4	5
Opportunity cost	82	102	122	82	102	122	82	102	122
Maintenance cost	122	222	266	122	222	266	122	222	266
TOTAL COSTS									
Riparian woodland	5	6	7	5	6	7	5	6	7
Broadleaf woodland									
30%	64	80	123	64	80	123	64	80	123
64%	133	166	198	133	166	198	133	166	198
100%	202	322	386	202	322	386	202	322	386
100 % broadleaf woodland + riparian woodland	207	328	393	207	328	393	207	328	393

Table 3-4 continued

	2016			2040			2080		
	Low (£ thousands per year)	**Central** (£ thousands per year)	**High** (£ thousands per year)	**Low** (£ thousands per year)	**Central** (£ thousands per year)	**High** (£ thousands per year)	**Low** (£ thousands per year)	**Central** (£ thousands per year)	**High** (£ thousands per year)
NET BENEFITS									
Riparian woodland	51	90	122	44	81	118	43	79	118
Broadleaf woodland									
30%	279	593	881	275	585	873	274	585	872
64%	586	1247	1923	589	1244	1918	589	1243	1916
100%	916	1883	2929	919	1886	2924	919	1880	2922
100 % broadleaf woodland + riparian woodland	961	1965	3050	961	1966	3051	963	1966	3048
BENEFIT COST RATIO									
Riparian woodland	11,1	15,6	18,1	9,7	14,1	17,5	9,5	13,7	17,5
Broadleaf WOODLAND									
30%	5,3	8,4	8,2	5,3	8,3	8,1	5,3	8,3	8,1
64%	5,4	8,5	10,7	5,4	8,5	10,7	5,4	8,5	10,7
100%	5,5	6,9	8,6	5,5	6,9	8,6	5,6	6,8	8,6
100 % broadleaf woodland + riparian woodland	5,6	7,0	8,8	5,6	7,0	8,8	5,7	7,0	8,8

Table 3-4 continued

The positive eco-system services values for the riparian woodland are mainly driven by the status change of the water body under the Water Framework Directive (WFD) (water quality in the table), climate regulation and recreational values. The water quality values are high as the calculation takes account of the population within a 20-mile radius of the water body which includes Edinburgh, a major city. The climate regulation values are driven by the prices of carbon, which vary between scenarios. Similarly, the scenarios for recreational values differ substantially (the high value is 13 times the low value) creating the disparity in the results across the scenarios. The results for the riparian woodland demonstrate, however, that the project achieves its main purpose, namely providing benefits under the WFD, under all scenarios. Given that a range of ecosystem services could not be monetised, we can be confident that the riparian woodland exhibits a strong positive NPV under all scenarios showing that the Eddleston Water measures were worthwhile. For the broadleaves, the positive ecosystem benefits are also driven by climate regulation, recreation and aesthetic value. The per hectare estimates do not reflect decreasing marginal values which may apply in particular with respect to the 64 % and 100 % afforestation. Nevertheless, even a 100% afforestation refers only to a relatively small area (the catchment is about 16 kilometres long and on average 4 km wide), and while it is unlikely that the estimates for the high scenario are an appropriate, we would not expect negative values due to the afforestation.

Of the costs considered, maintenance is the highest cost based on fixed payments per hectare every five years. The overall cost for all measures but riparian woodland is lower in 2080 compared with 2040 as those measures require maintenance which is discounted more heavily as we advance further in time. Opportunity costs are low per year. Due to the currently low prices for lambs based on 2012 values. The calculation assumes that the prices will remain constant over the appraisal time frame, which depends on supply and demand both in national and international markets and on the EU Common Agricultural Policy due to subsidies (Lefebvre et al. 2012), which may change over time.

3.5 Discussion

For the small village in our case study, we find that afforestation can play a role as a climate change adaptation strategy to flooding for high frequency events, i.e. with a return period of 1 in 20 years (which are likely to become even more frequent in the future). However, its impact on what we currently might describe as medium frequency events (i.e. 1/20 year events and lower) will decrease. In our case study, we find the peak flows of different flood events under climate change will increase and consequently cause more damage. This means, on the one hand, that flood management measures including NFM play an increasingly important role, but on the other hand we observed that the flow regulating effects of afforestation as a NFM decrease as the peak flows increase. Note that the full flood regulation benefits are only realised about 15 years after implementation. This is important, particularly in catchments with communities at flood risk for which there is already stakeholder demand for risk reduction, even at current levels of exposure (Harries and Penning-Rowsell 2011).

Taking into account the net costs in addition to the net benefits, afforestation, when considered exclusively as a NFM measure, provides positive NPV only for riparian woodland in our case study. Thus, with respect to flood regulation, it appears that the marginal benefit does not exceed the marginal cost of planting further forest beyond the currently planted riparian woodland even under climate change.

However, afforestation delivers positive NPVs for all afforestation scenarios if further ecosystem services are considered. This shows that there is a strong case for implementing such measures when the project objectives include multiple ecosystem benefits.

The impact of the discount rate on the results should also be noted. This study used the recommended discount rate in the Green Book, 3.5 % for 30 years and due to a decrease in time preference, 3 % after that. A higher discount rate would decrease the yearly NPV significantly making the investments less attractive. Also, a higher discount rate will lead to a stronger decrease in net benefits than in net costs as the planning and investment costs are incurred in the present and are therefore not discounted whereas the benefits accrue from year 2012 onwards.

Modelling the impact of afforestation scenarios on ecosystem services and determining their economic impact is only the first step for possible changes in land use management. Whether the aim is to reduce flooding, improve water quality, increase carbon sequestration or achieving multiple aims, such measures place yet another demand on rural land use. This requires long-term planning and contracts between the authorities (representing the public beneficiaries) and private landowners and managers who incur the costs to deliver these new public benefits beyond the current five year grant horizons to provide planning security (Werritty et al. 2010). For example, given the substantial changes to the catchment through 100 % afforestation, which would include negotiating with numerous landowners, the realisation of such a scenario appears unlikely even though the benefits are substantial.

A number of caveats need to be mentioned. Uncertainty plays a major role in the assessment and should be taken into account when interpreting the results. There is the uncertainty of the downscaled climate change projections (Dessai and Sluijs van de 2007), which we have tried to accommodate by using different percentiles to reflect the range of potential outcomes. Determining peak flow in a baseline scenario is not always an easy task due to very limited samples of high flow events but there are also uncertainties in the hydraulic analyses when converting discharge to flood depths (Arnell 1990). Certainly, modelling of complex NFM measures and their impact on peak flow increases uncertainty. Also, the outcomes of the damage calculation are influenced by the chosen approach (Merz et al. 2010). Finally as noted, there is great uncertainty attached to the economic value of ecosystem services of forests (under climate change) which is partly represented in low, central and high values.

3.6 Conclusion

Chapter 3 provided a cost-benefit analysis of the impacts of the NFM measure afforestation on peak flows under climate change and on further ecosystem services in a small rural catchment in Scotland. The analysis allowed integrating climate change uncertainty through different climate change scenarios. While this is not an application of a robust decision-making per se (as the likelihood of the different scenarios cannot be determined and no implementation be preferred over another), the case study showed the added value of considering uncertainty in the analysis. It showed the range of possible outcomes and highlighted that all flooding will likely become more severe under all climate change scenarios and thus provides additional information to a decision-maker. The chapter specifically found significant positive NPV for all considered scenarios with the largest NPV provided by a combination of 100 % afforestation of the catchment and riparian woodland along the river. The benefits are driven mainly by ecosystem services other than flood regulation. For flood regulation, we found a substantial increase of damage costs under climate change in particular which highlights the need for flood protection. All afforestation scenarios provide some flood regulation benefits, which increase with the degree of afforestation and are greater for higher frequency flood events. We conclude for our case study that afforestation, when considered exclusively as a NFM measure, provides a positive NPV in some cases, but delivers positive NPVs for all afforestation scenarios if further ecosystem services are considered, increasing the benefit-cost ratio favourably. Economic appraisals aim to include all accrued costs and benefits to reflect the true NPV of a policy to the public. We therefore suggest considering further ecosystem services beyond flood regulation for the appraisal of NFM to enable policy-makers to make informed decisions with regard to investment in NFM.

4 Robust climate change adaptation: applying simplified real options analysis to afforestation as a flood management measure

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Ruth Dittrich is the main author of chapter 4. She conducted the literature research, developed (the majority) of the method, carried out the calculations and provided the discussion.

Adam Butler supported the work on the chapter by co-jointly developing with Ruth Dittrich the method on calculating the transition probabilities as well as writing code in R to extract the relevant data from UKCP09 climate change data for further data analysis.

Tom Ball provided the information from the hydrological analysis.

Anita Wreford and Dominic Moran provided feedback on the content and structure of the drafts of chapter 4.

The aim is to publish chapter 4 in a peer-review journal.

4.1 Abstract

Climate change uncertainty makes decisions for adaptation investments challenging, in particular when long time frames and large irreversible costs such as for flood infrastructure are involved. Often the costs will be immediate and clear, but the benefits may be uncertain and only occur in the distant future. Robust decision-making methods under uncertainty, such as real options analysis (ROA), handle uncertainty better and are therefore useful to guide decision-making for climate change adaptation. ROA allows for learning about climate change by developing flexible strategies that can be adjusted over time. Practical examples of ROA to climate change adaptation are still relatively limited. We propose a simplified application that makes use of the freely available climate data of the UKCP09 weather generator and can be implemented in spreadsheet format. The application is for

afforestation as a natural flood risk management measure (NFM) in a catchment in the Scottish Borders. NFM measures are increasingly promoted as alternatives to hard engineered flood management measures as they are generally less disruptive and less costly. The obtained strategy is driven mainly by the high maintenance cost of afforestation which results in postponing the investment as much as possible.

4.2 Introduction

The 2014 IPCC summary for policy makers identifies increased harm and economic loss from inland flooding to be among the eight key risks of climate change with potentially severe consequences for humans and socio-ecological systems. The identification of key risks is meant to help policy makers prioritise investment in climate change adaptation, however it is challenging to make precise recommendations for adaptation investments to reduce vulnerability to flood risk.

The costs may be immediate and clear while the benefits are uncertain and may only accrue in the distant future. The uncertainty stems from a number of sources. One is the natural variability and downscaling of climate models: the models used to explore climate change impacts on flooding are usually set up for a larger spatial scale than for the decision-making required (Towler et al. 2010). The evidence on changing flood risk and extreme flood events in river basins specifically is inconclusive (Bruin 2012). Further, the unknown extent of mitigation in the future, socio-economic changes which may increase or decrease the value of assets at flood risk and the preferences of future generations add to the uncertainty (Burke et al. 2016; Dessai and Sluijs van de 2007). Thus, there is a dilemma when it comes to climate change adaptation. Adaptation action for flooding is needed, but the extent remains unclear due to the uncertainty surrounding climate change impacts.

As discussed in Chapter 2, this poses difficulties to policy-makers seeking guidance on economic appraisal of flood management structures. As the effects of climate change are uncertain, decision-makers may be reluctant to invest in additional flood protection measures, with possibly high and irreversible cost. Yet at the same time, inaction and under-investment may lead to potentially severe flood damages, and delayed action may be even more costly.

The limitations of traditional decision-making approaches for investment appraisal in the context of climate change have been recognised by many decision-makers and governments. Alternative decision making approaches to appraise and select adaptation options are therefore being explored, both in the academic and policy literature (Dessai and Hulme 2007; Dessai and Sluijs van de 2007; European Commission 2013a; Fankhauser et al. 1999;

Hallegatte and Corfee-Morlot 2011; Hallegatte et al. 2012; Lempert and Schlesinger 2000; Ranger et al. 2010; UNFCCC 2009; Watkiss et al. 2014; Watkiss et al. 2009).

Robust decision-making tools under uncertainty to guide investment under uncertainty

Robust decision-making tools under uncertainty aim to incorporate uncertainty in adaptation investment appraisal, by selecting projects that meet their purpose across a variety of plausible futures (Hallegatte et al. 2012). Generally, robust approaches do not assume a single climate change forecast but integrate a wide range of climate scenarios through different mechanisms to capture as much as possible of the uncertainty on future climates (for an overview of different robust methods under uncertainty see Dittrich et al. (2016b)).

Real options analysis (ROA) is one robust decision-making tool under uncertainty that extends the principles of cost-benefit analysis (also assuming risk neutrality of the decision-maker) of a now or never decision by allowing for learning. The associated policies or actions can be adjusted over time when additional information about climate change impacts becomes available. ROA originates from financial options (Black and Scholes 1972; Cox et al. 2002; Dixit and Pindyck 1994; Merton 1973) and has been further developed for investment and engineering projects since the 1990s (Trigeorgis 1995). Real options can be "on" or "in" a project. When talking about ''on'' a project, this has a time implication: delaying or modifying part or all of an investment until new information becomes available for instance to expand or decrease or switch inputs/outputs. Real options ''in'' projects are technical engineering and design adjustments enabling options in operations that require the characterisation of interdependency/path-dependency amongst options (Cardin et al. 2013; Wang and De Neufville 2005). The options relate to the technical characteristics of the system, for example, a building might be designed such that air conditioning can be more easily added later if required. Thus, in addition to sequencing the investments time-wise, the options need to be designed such that they can be sequenced in a technically feasible way.

The learning in ROA is based on an uncertain underlying parameter. In the context of flooding and climate change this will for example be rainfall or sea level rise. Due to climate change (and changes in land use and river basins), hydrological variables will no longer be reliably constant and past hydrologic data do not necessarily provide a good indicator of future conditions, i.e. non-stationarity applies (Milly et al. 2008). Therefore a specific return period of a 1 in X year event based on historical data will not deliver the required standard over time, for example, a 1 in 100 year event may become a 1 in 75 year event in the future. In ROA, the uncertainty of the hydrological variable - at least with respect to climate change - is assumed to resolve with the passage of time due to increasing knowledge. For instance, the confidence in changes of rainfall extremes and related flood risk under climate change will likely increase over time as time series grow longer, as 'low-data' methods are developed and as model uncertainties in climate and hydrological models are reduced (Cunha et al. 2011; Lenderink et al. 2007; van Der Pol et al. 2015; Wagener et al. 2003). ROA takes advantage of this assumption that the uncertainty is dynamic rather than deep and provides strategies that can be adapted in a changing context.

ROA is suited for (partly) irreversible investments with long life times and sensitivity to climate conditions when there is a significant chance of over- or underinvesting combined with an opportunity cost to waiting, i.e. if there is a need for action in the present (Arnbjerg-Nielsen 2012). If the investment was partially or completely reversible, i.e. no sunk cost was incurred, there would be no value in delaying the investment or setting it up with flexibility. However, most investments include fixed costs such as planning costs. Fixed costs are also the reason why incremental investments, e.g. annual in reaction to observed changes in the climate, is inadvisable as with every investment, fixed costs will have to be paid and cannot be recovered. Given that flood and water management infrastructure often has these characteristics, ROA is an appropriate tool for analysis in this field.

Case studies of ROA include investment in coastal protection, both real "on" options (Linquiti and Vonortas 2012; Scandizzo 2011) and real "in" options such as for the Thames Estuary, England (Woodward et al. 2011). Gersonius et al. (2013) investigated the added value of real "in" options with respect to investments in urban drainage infrastructure in West Garforth, England. Several studies have examined water resource management under climate change. Jeuland and Whittington (2013) combined a real options and robust decision-making approach (Lempert et al. 2006) to guide water resources infrastructure investments and operating strategies for multipurpose dams along the Blue Nile in Ethiopia. Hobbs et al. (1997) considered water resource investments for the Great Lakes region, USA using Bayesian Analysis and Haguma et al. (2015) optimise for the long-term planning of water resources systems and the mid-term operations for optimum hydropower production for the Manicouagan River basin in Quebec, Canada. Van der Pol determined phased investments for dikes (2014) and storage basins in a Dutch polder (2015). All studies show that flexible strategies are superior to inflexible strategies. De Neufville and Scholtes (2011) estimate that flexibility (for real "in" options) can bring expected performance improvements ranging between 10 and 30% compared to standard design and evaluation approaches.

In this article, we propose a somewhat simplified ROA to make the tool accessible to policy makers and to potentially increase its use for climate change adaptation to flood risk. Real options analysis has not been widely used in actual policy making, probably because it is relatively complex to implement. It requires an understanding of financial theory and relatively advanced mathematical techniques such as stochastic dynamic programming (van der Pol et al. 2014) or genetic algorithms (Gersonius et al. 2013). Furthermore, statistical data on the change of the uncertain parameter is required which may not be easily obtained.

ROA applied to Natural Flood Risk Management

This chapter demonstrates the approach with an application to afforestation as a natural flood management (NFM) measure in a medium size catchment in Scotland. NFM involves the utilisation or restoration of 'natural' land cover and channel-floodplain features within catchments to increase the time to peak and reduce the height of the flood wave downstream (Environment Agency 2010). NFM is widely recognised as an option to reduce flooding whilst achieving multiple benefits throughout the catchment such as ecosystem services including provision of habitat while 'hard' engineering 'solutions' have often significant environmental impacts because they disrupt natural flow and storage processes (Iacob et al. 2014). NFM including afforestation is rising rapidly up the policy agenda across Europe because of its potential to buffer the effects of climate change (European Commission 2009; European Commission 2012; Scottish Government 2009b).

Over time trees develop a complex root system (growing and dying) creating preferential pathways for water flow and promoting higher infiltration rates (Archer et al. 2002; Schwärzel et al. 2012). Combined with higher rates of interception and evapotranspiration it results in reduced runoff and sediment production (Calder 1990). Afforestation can lead to a decrease in flood peak or changes in flood risk probability depending on the degree of forest covers in the catchment (Bulygina et al. 2009; Calder and Aylward 2006; Francés et al. 2008; Naden 1996; Nisbet and Thomas 2008; Odoni and Lane 2010; Thomas and Nisbet 2007; Wheater et al. 2012; Wheater et al. 2010). The relationship is positive with an increasing rate, however the effectiveness diminishes as storm intensity increases and is more pronounced for small catchments (Iacob et al. 2014). The performance of afforestation measures in reducing the flood peak depends on several factors, notably the previous land use and soil characteristics (Hümann et al. 2011) as well as spatio-temporal variations in rainfall and runoff (Pattison and Lane 2012).

Chapter 4 applies the robust decision-making tool under uncertainty ROA to the same case study area with the same climate change scenarios as Chapter 3. The results can therefore provide a direct comparison of the added value of the robust decision-making tool under uncertainty for climate change adaptation. Additionally, Chapter 4 offers a simplified application of a robust tool under uncertainty as suggested by the results in Chapter 2 to improve the accessibility of the tool to practitioners and explore the applicability of ROA to NFM. We develop a flexible real 'on' options strategy for planting forest with the aim to minimise the life cycle cost of a system to avoid a flood with a return period of 1 in 20 years.

The remainder of the paper is structured as follows: section 4.3 describes the methodology for our case study. Section 4.4 presents the results followed by a discussion and conclusion in section 4.5.

4.3 Methodology for the case study

The case study area is the Eddleston Water catchment of 69 km^2 in the Scottish Borders, UK. The Eddleston Water is a small tributary of the River Tweed, flowing 17 km north to south before reaching the main river Tweed in the town of Peebles. The village of Eddleston (940 inhabitants) and further downstream the town of Peebles (7853 inhabitants) which are both situated at the Eddleston Water are at risk of riverine flooding. Some NFM measures have been implemented in the case study to reduce the risk of flooding (and improve water quality) including afforestation with broadleaves (Tweed Forum 2015).

The challenge is to identify how to sequence the flood risk management measure so that it prevents flooding under a 1 in 20 year rainfall event[10] in a way that minimises the expected lifetime cost of the system. In this case the flood risk management measure is the hectares of trees planted. A 1 in 20 year return period today may correspond to a 1 in 15 year return period in the future. Thus, keeping a 1/20 standard over time requires increasing flood protection infrastructure at the same or similar rate as the return period changes. The aim is to avoid both under and over-investment, which results either in a flood protection standard below the 1/20 year flood event or flood regulation capacity above the required standard. The decision problem can be structured as follows (Gersonius et al. 2013):

1. Determine the parameters to be learned about
2. Specify the decision-tree
3. Identify the potential options
4. Formulate the optimisation objective
5. Solve the optimisation problem

4.3.1 Determine the parameters to be learned about

In a first step, the climate change parameters that we expect to learn about are determined. The parameters will depend on the specific case study. Here the focus is on riverine flooding which is influenced by rainfall as a climate variable, specifically high intensity rainfall in a relatively short time (24 hours or less) as defined by the rainfall patterns in the case study area. The data used in this study is provided by the UKCP09 (Murphy et al. 2009). The publicly available dataset provides rainfall data across the UK, which is based on perturbing the existing Weather Generator[11] according to the probabilistic projections for climate change scenarios. Thus, the data provides a range of possible outcomes of future rainfall intensities (conditional on low, medium and high emission scenarios) and it is precisely those outcomes, we hope to learn about. Based on the actual changes in rainfall intensity that we experience (or learn about through improved modelling) in the future, the adaptation strategy can be adjusted in the most efficient way based on the strategy provided by the real option analysis.

[10] The 1/20 standard was chosen as 1) no flooding occurs for a rainfall event with higher return periods and 2) flooding can be avoided by afforestation in the catchment given the peak flow of such an event.

[11] Weather generator use weather data and random number sampling to produce long time series of statistically plausible daily and hourly weather data.

4.3.2 Specify the decision tree

The decision problem can be demonstrated in a decision tree (Figure 4-1). The branches represent the potential climate change paths, i.e. the expected change in rainfall intensity for different futures. The knots describe the flood management measure implemented depending on the different climate outcomes. We specify a decision tree with two decision points (2016 and 2040) and four potential outcomes at each decision point as a compromise between adequately representing the climate uncertainty while reducing the complexity of the calculations.

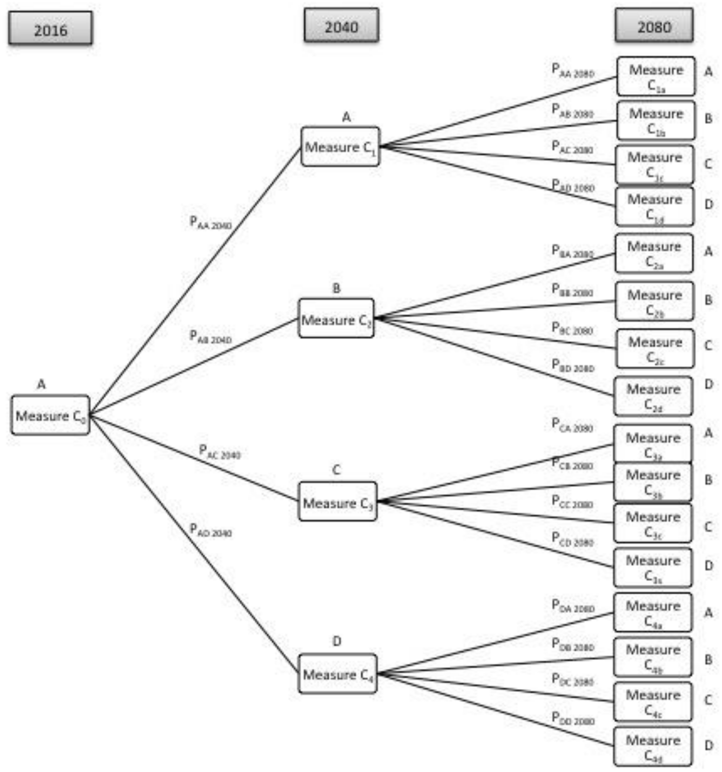

Figure 4-1 Decision tree for a real options analysis

Describing the different branches in the decision tree (determining transition probabilities) is one of the main challenges in applications of real options to climate change as it is not clear that probabilities for different paths on a case study level can be determined. Some authors (Gersonius et al. 2013; Linquiti and Vonortas 2012; Scandizzo 2011) assume that climate change follows the stochastic process Geometric Brownian Motion (GBM) also used in finance applications. Others use a moving window approach (van der Pol, 2015) or related to this Bayesian learning based on observed changes in rainfall/water level (Haguma et al. 2015).We apply an approach related to Woodward et al. (2011), which used the underlying distribution of the UKCP09 climate change data (Murphy et al. 2009) and is thus solidly based on the behaviour of climate projection models. Furthermore, it can be relatively easily implemented. The data is conditional on the high, medium and low scenarios. As no information is available on the likelihood associated with the climate change scenarios, we have chosen the medium scenario to represent the central outcome. However, given the recent evidence on future global emissions (Le Quéré et al. 2015), we must assume that a medium scenario is likely to be a conservative estimate. Part of the rainfall data analysis process is illustrated in the flow chart of figure 4-2.

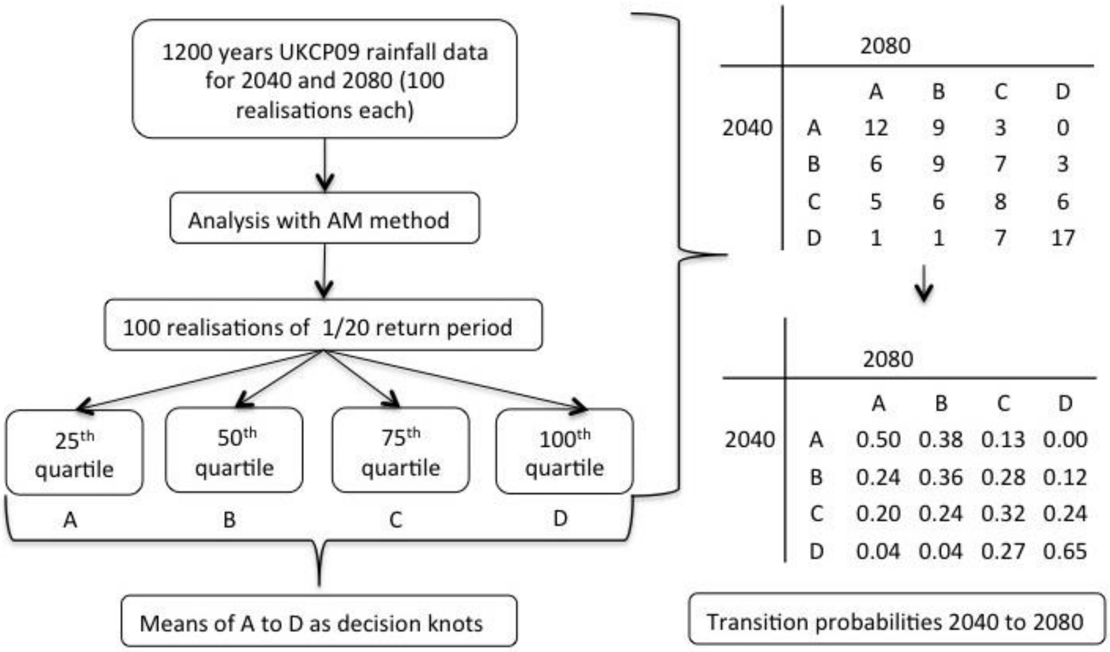

Figure 4-2 Calculation of transition probabilities and rainfall intensity of a 1/20 year return period from 2040 to 2080.

We downloaded 40 sets of 30-years hourly time series of rainfall (with the same model IDs) for the case study area with 100 realisations in each set for the 1990s (the baseline period)[12], the 2040s and the 2080s. This equals 1200-years of hourly time series for each of the 100 realisations to obtain a good estimate of the distribution of the models. The data was

12 We assume the baseline represents 2016 flows, which was validated against (more recent) flow observations from the case study area.

analysed with the annual maximum method (AM) (Coles 2001) in the R package extRemes (Gilleland 2015) to obtain the vector of distribution parameters $\varphi_t = (\xi_t, \sigma_t \text{ and } \mu_t)$ of the rainfall distribution for the baseline, 2040 and 2080, where ξ_t is the shape parameter, σ_t is the scale parameter, and μ_t is the location parameter.

The distribution parameters were used to obtain 100 different rainfall intensities (based on the 100 realisations) of the 1 in 20 flood for the future periods. For the baseline period, only one rainfall intensity was obtained for all realisations as they all originate from the same distribution and its variability reflects natural rather than climate variability. The baseline data represents the current rainfall intensity of a 1 in 20 years return period and is represented by the initial knot in the decision tree in Figure 4-1. To obtain the other 20 knots (4 knots for 2040 and 16 knots for 2080) in the decision tree, the 100 return levels obtained for each 2040 and 2080 were respectively split into quartiles and the mean return level estimate of each bin represents the knots, i.e. the rainfall intensity of a 1 in 20 rainfall event in different futures. Thus, the climate change uncertainty (characterised by the distribution of the 100 return periods) is represented by the quartiles. The four blocks of the four in 2080 are identical as these are the outcomes projected by the UKCP09 data for 2080.

We next determine the transition probabilities. For each return period estimate, we know which bin (labelled A to D) it belongs to for the baseline, 2040 and 2080. (We assume that all baseline runs are in one bin A.) For a particular estimate, we might say that it is AB, i.e. implying that this particular return period lay in the 25th quartile of the 2040 distribution and within the 50th quartile of the 2080 distribution. As a result we obtain a list of 100 two letter-codes, characterising each of the runs for each of the three time periods, whose frequencies are entered in a transition matrix as shown in Figure 4-2. Each row is scaled to sum to one by dividing each combination by the sum of its row to obtain the transition probabilities. For example, going from 2040 to 2080, we observe in Digure 4-2 that the extreme outcomes such as moving from A to D ($p = 0$) or D to A ($p = 0.04$) are less likely than staying on the same climate path such as BB ($p = 0.36$) or CC ($p = 0.32$).

4.3.3 Identify the potential options

Options for building in decision flexibility depend on the problem at hand. Here, the flexibility comes from sequencing the planting of different hectares of the NFM measure afforestation with the full catchment and maximum afforestation corresponding to 6900 hectares. Our hydrological analysis was carried out with the hydraulic modeling system HEC-HMS (see Chapter 3 for further explanations about the model). Figure 4-3 shows the reduction in peak flow by implementing different levels of forest cover based on different rainfall intensities for our case study. Based on scenario runs of the hydrological model, we fitted functions to describe the relationship between forest cover and peak flow. In total eight different functions are specified for the eight rainfall intensities (4 in 2040 and 4 in 2080) in order to determine how many hectares to plant under the peak flows corresponding to a 1/20 year event over time. The results can be directly used in the cost function.

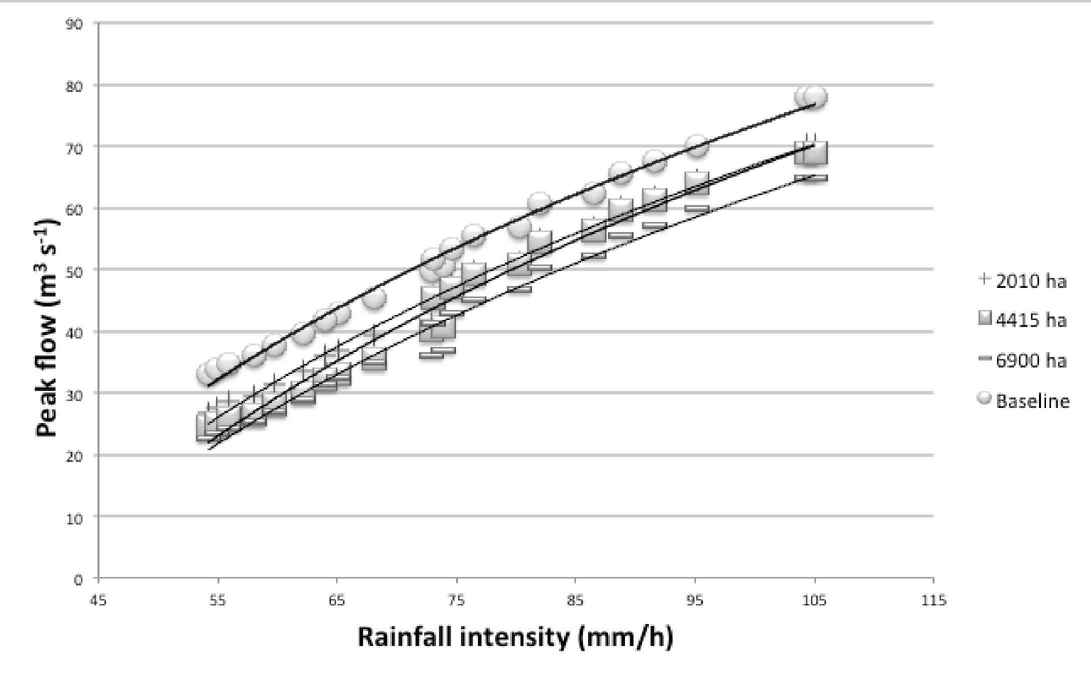

Figure 4-3 Rainfall intensity (mm/h) and resulting peak flow (m^3s^{-1}) for the baseline and four afforestation scenarios (2010, 4415, 6900 ha) in Eddelston Village.

4.3.4 Formulate the optimisation objective

We aim to find a cost-minimising investment strategy z_t of afforestation up to the last year of the time horizon Y_t which equals 75.

$$C = \min_{z_t} \sum_{y_t=1}^{Y_t} \frac{I(z_t) + O(x_t) + D(x_t)}{(1+\delta)^{y_t - y_1}} \quad (4)$$

where C is the net present cost of total investment, operation and maintenance as well as damage costs. Investment costs are described by function $I(z_t)$, and annual operation and maintenance costs by function $O(x_t)$ and damage cost by $D(x_t)$. Costs are discounted at rate δ based on the recommendation of the UK Green Book (HM Treasury 2003). Damage occurs if an insufficient level of trees was planted. The decision variable is z_t (e.g. investment in additional afforestation at the decision nodes and x_t is the stock variable, which is the total of stock of afforestation at year t. Additional investment z_t is realised at three decision points, at time t = 1, 2, 3 (which correspond to 2016, 2040 and 2080), i.e.:

$$x_{t+1}: x_t + z_t \quad (5)$$

A reliability constraint is applicable during the compliance period [1,2,3],

$$q_{tu}(x + z\ ) \leq \propto \quad (6)$$

where $\propto$ is a pre-defined standard and q_{tu} is an estimate of the 1-in 20 year return period of flow at time t based on a particular climate u.

We apply figures from the case study areas to inform our cost functions. The costs for implementing the afforestation measures can be divided into investment cost I(z) and maintenance as well as opportunity costs O (x). Investment costs include fixed costs such as facilitation services (for example to negotiate with land owners) as well as fees and the variable planting costs and have been found to be logarithmic, i.e. the cost increases at a decreasing rate and doubling the forest size will lead to less than double the cost.

$$I(z) = \begin{cases} \mathrm{a} + \mathrm{b}\ln(z) & if\ z \geq 1 \\ 0 & if\ z < 1 \end{cases} \quad (7)$$

Maintenance costs m refer to thinning every 5 years and are assumed to be constant and linear depending on the hectare size. Opportunity costs n refers here to forgone use of land for sheep grazing, which is (mostly) the land use of the (modelled) afforested areas and is also assumed to be linear.

$$O(x) = mx + nx \tag{8}$$

The transition probabilities that we determined in 5.3.1 can be described as follows:

$$p_{ijt} = P(u_{t+1} = j | u_t = i) \tag{9}$$

where u_t is the categorical variable determining which of the four possible climates (expressed as 1-in-20 year return levels) is to be used at the decision points t=1, 2, 3. U_t can take value 1,…4 depending on the number of bins at t. At the first time point, t=1, there is only one return level so $u_1 = 1$.

The optimisation problem can be formulated as follows:

$$J_t(j, x) = \min_z \left(\frac{I(z) + O(x + z) + D(z)}{(1 + \delta)^{y_t - y_1}} + \sum_j p_{ijt} J_{t+1}(j, x + z) \right) \tag{10}$$

$$s.t.\ q_{tu}(x + z) \leq \propto$$

where J_t is the value function which describes the best possible value of the objective (i.e. the minimised cost), written as a function of z and where t=1, 2, 3 and hectares planted are $z = 1, \Delta z, 2\Delta z, \ldots, 6900$. Hectares planted up to 6900 ha were considered in steps of 1 (Δz).

4.3.5 Solving the optimisation problem

This formulation can be solved by dynamic (stochastic) programming, however we show that an optimisation problem of this degree of complexity as this one can also be solved in a spreadsheet using backward induction.

The cost parameters used for the case study were obtained from actual figures from planting different plots of trees in the case study area and are specified with further parameters in Table 4-1. The maintenance cost is £282 per hectare every five years. This is what farmers are currently paid to manage forest planted for NFM purposes in the case study area. The damage cost for a 1/20 years event under the different quartiles was obtained from Dittrich et al. (2016a)[13]. QMS (2014) figures on sheep profitability, suggest a net margin of £26 per

[13] Alternatively, a very high (hypothetical) damage cost can be assumed to avoid that those strategies under which damage occur are chosen (Gersonius et al., 2013).

ewe for improved pasture for the past years which we apply for 2016. We further assume that 1.5 ewes can be fed on one hectare in the case study area (Scottish Government 2015).

We assume that the trees immediately have their full flood regulation effect but in practice, it can take between 5 -15 years for a full effect on the hydrological cycle (Farley et al. 2005).

Parameter		Value (in 2012 prices where applicable)
Constant (describing fixed cost)	a	£8552.2
Constant (describing variable cost)	b	£5181.4
Maintenance cost	m	£282
Opportunity cost	n	£39
Discount rate (until project year 30)	δ	3.5%
Discount rate (after project year 30)	δ	3%
	∝	36 $m^3 s^{-1}$

Table 4-1 Case study parameters

In a first step, we calculate the net cost for all 256 (4^4) paths assuming they were going to be implemented. Figure 4-4 shows part of the decision tree; the branches of path 1 are a dotted line. If path 1 was carried out, sufficient trees would be planted in 2016 (investment decision I1a) to prevent flooding of a 1/20 year event associated with bin A (25^{th} quartile) in 2040. Getting to 2040, the 1/20 year event turns out to correspond to bin A (outcome N1a), so no further trees need to be planted to correct for a wrong decision in 2016 (I1=N1), and no damage cost is incurred. Instead, further trees are planted to prevent flooding of a 1/20 rainfall event in 2080 corresponding to bin A (25^{th} quartile) in 2080 (I2a). In 2080, this choice turns out to be correct (N2a) and no further trees need to be planted (I2=N2). In 2080, we assume the uncertainty has resolved and the final planting decision based on the climate outcome in 2080 can be made. The net cost of path 1 (P_1 cost in figure 4-4) will therefore be the discounted cost of planting $I_1 + I_{2a}$. This includes the maintenance and opportunity costs, which depends on hectare planted. The cost of I_{3a} is not incurred, as no additional trees are required as the right decision was made in 2040. The net cost of path 2 (P_2 cost in figure 4-4) is identical to path 1 with the only difference that in 2080, the 1/20 years event corresponds to bin B (50^{th} quartile) (N2 ≠I2), which means that additional trees need to be planted in 2080 to make up the difference between the return level of the 25^{th} and 50^{th} percentile and associated damage (damage of a 1/20 years event under the 50^{th} quartile minus the damage of a 1/20 year event under the 25^{th} quartile)[14] occurs twice in the 40 years.

[14] No damage is incurred in the case study are from a flood event higher than a 1/20 RP.

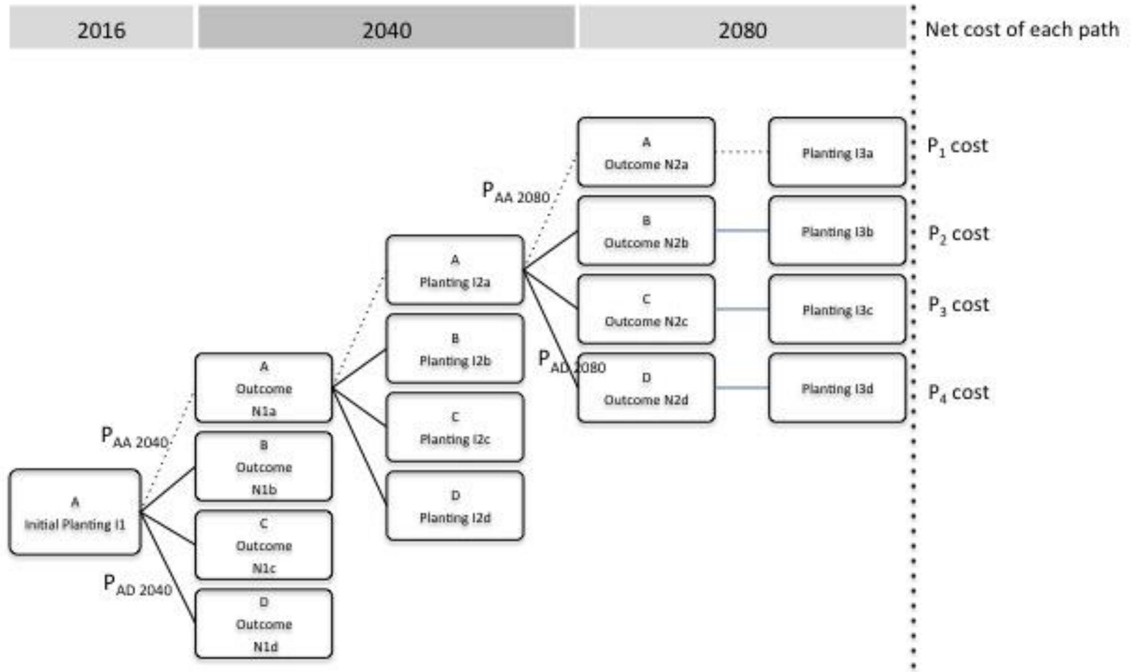

Figure 4-4 Illustration of backward induction for the decision problem

In a second step, we carry out the backward induction. We start by analysing the second investment decision made in 2040 for the 4 blocks (of 4 options each). At this point, we know which option to choose depending on the outcome of N_1. For each block, we have the choice between making investment I_{2a}, I_{2b}, I_{2c} and I_{2d}, i.e. planting for what corresponds to the 25th, 50th, 75th 100th quartiles of the 1 in 20 years event rainfall intensity in 2080. For the first block, the following outcomes might realise N_{2a}, N_{2b}, N_{2c} and N_{2d} with the probabilities p_{AA2080}, p_{AB2080}, p_{AC2080} and p_{AD080} respectively. Thus, if implementing the option for the 25th quartile of rainfall intensity, the expected cost equals $p_{AA2080}P_1 + p_{AB2080}P_2 + p_{AC2080}P_3 + p_{AD2080}P_4$. We can calculate the expected cost for implementing the other three options accordingly and will choose the outcome with the lowest cost. This process is carried out for all 4 blocks at decision node I_2. The same procedure is carried out for the investment decision I_1. We find the lowest net cost by multiplying the probabilities $p_{AA2040}...p_{AD2040}$ with the respective lowest outcome for I_2 and comparing them.

4.4 Results and discussion

Initially only investment I_1 is implemented in 2016. Subsequently a set of further measures can be implemented during the second period starting in 2040 determined by the climate outcome of the first period. Thus, the optimal investment decision today is influenced by the possibility of the decision-maker to adjust their decision at a future moment in time based on the change of the peak flow of a 1/20 years event in the future.

In our case, the initial decision would be to plant for the 25th quartile in 2016, and the decision in 2040 depends on the outcome in 2040. For all cases, the second option will be to plant 25th quartile. If the initial recommendation would have been to plant for the 75th quartile, different recommendations would have resulted as shown in Table 4-2.

Decision I_1 (quartile)	Outcome N_1 (quartile)	Decision I_2 (quartile)
25th	**25th**	**25th**
	50th	**25th**
	75th	**25th**
	100th	**25th**
50th	25th	25th
	50th	25th
	75th	25th
	100th	25th
75th	25th	50th
	50th	50th
	75th	25th
	100th	25th
100th	25th	75th
	50th	50th
	75th	75th
	100th	25th

Table 4-2 Flexible strategies for the case study

The cost of the expected flexible strategy is shown to be about 65 % cheaper (£5.3mil) than the worst-case strategy, (£15.6m), i.e. planting for the worst-case outcome in 2016, which is highly significant. The estimated maximum regret avoided (i.e. the maximum possible over-investment avoided) is equal to the net present costs of the static worst-case strategy minus the cost of the cheapest strategy that can be realised under the flexible strategy and amounts to about £13 million (84% of the static strategy).

Our results are driven by the high maintenance cost within the system relative to the damage cost for most configurations. There is thus an incentive to postpone investments as much as possible. In addition, the later the investment occurs, the more the costs will be discounted. The fixed (irreversible) costs (that occur with every investment) do not appear to play a major role, as there are only two investment decisions when fixed costs occur and they are low relative to the maintenance cost. A planting strategy with additional decision nodes allowing for more frequent planting would likely improve the strategy somewhat, however this would substantially increase the complexity of the problem to be solved.

The resulting strategy here suggests that waiting and choosing the most conservative strategy instead of investing for the worst case will lead to the lowest overall cost. It should be noted that in our configuration, we accept incurring flood damage, as this is cheaper than planting more trees to prevent flooding (based on actual damage cost). A policy-maker could choose the damage cost to be sufficiently high (not reflecting actual damage cost) to ensure that strategies that allow flooding will not be chosen, to ensure that the 1/20 flood return period standard is met (for most outcomes). For example, by increasing the damage cost 10-fold for each outcome, the initial investment will be to plant for the 50th percentile.

Our results show implicitly that if afforestation is considered only in terms of flood infrastructure, its cost does not actually exceed its benefit (which is damage avoided) as the strategy allows for the flooding to occur. We observe that the planting costs are low but the maintenance cost (based on per hectare subsidies currently paid to farmers for maintenance of managed forest) are significant over time (£10 mil for the worst case scenario or £133k per year) and drive the investment strategy. Thus, while afforestation may be cheaper initially compared to 'hard engineered' measures, if the maintenance cost cannot be brought down, it may not necessarily be a more cost-effective strategy than hard engineered measures for flood regulation only. Other NFM measures, for example retention ponds, will have a different cost structure with significantly lower maintenance cost nwrm(NWRM 2013)and might thus be more suited for flood protection and the application of ROA.

However, afforestation provides ecosystem services benefits such as carbon sequestration, recreation and habitat beyond flood regulation (Willis et al. 2003). These benefits were beyond the scope of the analysis but might alter the outcome of the analysis towards earlier investment and would provide a better estimate of the benefits accrued (see Dittrich et al. (2016a) for a CBA on the eco-system services of afforestation in the case study area).

We believe that the approach described to determine the best flexible strategy can be carried out by policy-makers if they have access to perturbed rainfall data and we thus provide a valid contribution to applied adaptation to climate change in the context of flooding. While the general mathematical description of the problem in section 5.3.3 may appear complex, a simplified version can be implemented with few resources.

In the UK, perturbed rainfall data is freely available in a user-friendly way through the UKCP09 weather generator data. We downloaded a large amount of data sets to ensure that we found the correct distribution of the rainfall but a good approximation can also be found with fewer sets. The analysis with the AM method is a standard analysis among hydrologists and can likely be carried out in the (flood) infrastructure department of a public authority together with the changes in peak flow of any measures implemented, in particular if the relationship between the measure analysed and peak-flow is well established (e.g. for retention reservoirs). With the results of the AM method, the transition probabilities can be easily calculated as described in section 5.3.1, which is often a major challenge in ROA. The cost of the measure can be obtained through quotes from different contractors. There might be historical data for the damage cost (under different peak flows) or it will require a damage analysis (in the UK for the example with the Multi-Coloured Handbook (MCH) (Penning-Rowsell et al. 2010). The calculation of the transition probabilities and the backward induction can be carried out in an excel spreadsheet. Taken together, the steps are labour-intensive but can be carried out without in-depth knowledge of advanced programming. Indeed, the greater challenge for any policy-maker may be to initiate policies which have a lifetime long beyond the current four to five years of a policy cycle.

A few caveats need to be mentioned. To assume that the return period changes significantly with a time step rather than slowly over time is simplistic. Certainly, the analysis could be enhanced by using continuous distributions for rainfall instead of point estimates and different forms of uncertainty resolution. However, we believe the information gained by this may not necessarily outweigh the added complexity given that we have aimed to provide a relatively accessible approach to ROA. Further, the analysis does not include possible changes in land-use (Ball and Green 2007), which may influence the flood patterns.

4.5 Conclusion

Chapter 4 has shown a simplified application of real options analysis as a climate change adaptation strategy using afforestation as a natural flood management measure in a case study in the Scottish borders. The aim was to minimise the life cycle cost of a system to prevent flooding of 1/20 years return period. The underlying idea of real options analysis is to delay costly irreversible investments (both fixed and maintenance cost) until further information emerges. Our analysis requires as inputs perturbed rainfall data as freely available from the UKCP09 weather generator, analysis of changes of peak flow under the measure implemented, cost structures for the measures to be implemented (including opportunity cost) and damage costs under different outcomes. The analysis can be carried out in an excel spread sheet with these types of input. Thus, Chapter 4 demonstrated that a simplification as suggested in Chapter 2 is feasible, however, the presented simplification is still labour intense. This highlights the importance of continued efforts to develop more robust tools under uncertainty which are easily accessible to decision-makers.

In our case study the results show that the least cost option is to plant for the most conservative climate change outcome in 2016 and for all possible outcomes in 2040 due to the high maintenance cost in the system, which incentivises postponing the investment and related mainteanance cost as much as possible. This shows as well that the cost of the NFM measures afforestation accrues mostly from maintenance and not from the initial investment (including fixed cost). The strategy developed here is significantly cheaper than the planting for the worst case scenario and shows for different configurations the potential for learning under climate change uncertainty as a way to allocate resources more efficiently. The result is in agreement with the results of Chapter 3 which suggests that afforestation may not be a suitable investment if only flood regulation benefits are considered on the benefit side. However, Chapter 4 highlights very clearly when the investment becomes worthwhile (i.e. at which level of maintenance and damage cost with the latter being directly linked to climate change impacts) and thus emphasises the importance of learning for robust adaptation decision-making.

5 The impact of flood action groups on the uptake of flood management measures

Ruth Dittrich, Anita Wreford, Adam Butler, Dominic Moran

Ruth Dittrich is the main author of Chapter 5. She carried out the literature research, the development of the survey and conducted the survey (with the support of the Scottish Flood Forum and local flood action groups). She analysed the data and authored the discussion.

Adam Butler supported the work by advising on the choice of the statistical model and wrote further R code for the revision of the chapter as a peer-reviewed article. He coded the imputation of missing data, linked it with the model selection process and coded the mediation analysis.

Anita Wreford and Dominic Moran contributed with feedback on structure and content on the drafts of chapter 5.

Chapter 5 is published as a peer-reviewed article in Climatic Change:

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5.1 Abstract

Private flood management measures can significantly reduce the risk from flooding. Understanding the factors that influence the uptake of household flood management measures has important implications for the design of measures to induce people to take charge of risk mitigation. We investigate the impact of flood action groups in communities in Scotland on uptake using a cross-sectional survey (n=124). These groups were formed in response to the threat from flooding in those communities, and offer information and training on household flood management measures. We investigate the uptake of four measures: insurance, flood warnings, sandbags and floodgates applying regression analysis. We use the theoretical framework of Protection Motivation Theory, and compare uptake of

the measures before and after the foundation of the flood action groups, as well as in the near future. The models show direct positive adoption effects for flood warnings, floodgates and to an extent for insurance, and indirectly through increased confidence of implementing and belief in the effectiveness of the measures. The effect is more pronounced if specific information on the measures was provided, indicating the importance of tailored content. We conclude that appropriately designed flood action groups can be a cost-effective way of increasing the uptake of household flood management measures, in particular in small communities where large engineering measures may not be financially viable.

5.2 Introduction

In Europe, storms and flooding are the most costly weather-related disasters, accounting for 77 % (€282bn in 2005 value) of economic losses due to extreme weather events between 1980 and 2006 (CEA 2007). Beyond the economic losses, the recovery stage for flood victims often has important repercussions on family, health and work situations. Climate change may increase the frequency of high impact events locally in the future (IPCC 2012) and this may be exacerbated by development of housing in flood-prone areas (Bouwer et al. 2010) as well as increasing impermeable surfaces that increase runoff hardscape such as streets and parking lots (Brattebo and Booth 2003). Taking the above described factors together, implementing adaptation measures against flooding should be considered in vulnerable areas. This may require public flood protection - for example through integrated flood management strategies on a national and international level (European Union 2007; Scottish Government 2009a) - but also adaptation measures implemented by households and firms where flood risk cannot be eliminated due to budget limitations. Private flood protection measures can reduce flood damage significantly (ICPR 2002; Kreibich et al. 2005) depending on the local conditions and the flood severity (Kreibich et al. 2015).

Yet practical experience suggests that households do not necessarily implement adaptation measures in order to increase their resilience to flooding (Bichard and Kazmierczak 2012; Kunreuther 1996; Peek and Mileti 2002). Research addressing household decision-making on flood prevention provides limited insights into the communication of flood risk (Dawson et al. 2011; Kellens et al. 2013; Meyer et al. 2012). There are an increasing number of studies highlighting the role of psychological factors in private adaptation to flooding in addition to risk perception and socio-economic variables. One approach, known as Protection Motivation Theory (PMT), attempts to reflect the main cognitive processes leading to the motivation to take protective action.

PMT suggests that individuals' decisions to take action is influenced not only by their evaluation of the physical risk, but also by their beliefs regarding the cost and effectiveness of the measure, as well as their confidence in implementing it. Several studies have found PMT a suitable framework for exploring flood adaptation behaviour, and that it can achieve a good fit with observed data (Bubeck et al. 2012b; Bubeck et al. 2013; Grothmann and Reusswig 2006; Le Dang et al. 2014).

Chapter 5 uses insights from PMT to explore the factors influencing the uptake of a range of household flood adaptation measures among 124 private households in Scotland. The Chapter therefore acknowledges that the top-down adaptation to flooding as discussed in Chapters 3 to 4 needs to be complemented by bottom-up adaptation, for example when the damage costs do not justify an investment in community level flood risk infrastructure as demonstrated in both Chapters 3 and 4 (when only the flood alleviation benefits of afforestation are considered). We add to the existing research by exploring how people's perceptions of the effectiveness of measures, and their confidence in implementing them, which - according to PMT - play an important role in determining flood adaptation behaviour can be positively impacted in order to increase further uptake. We specifically investigate the effect of flood action groups, which aim to demonstrate the effectiveness of measures and may raise people's confidence in applying them. These autonomous groups were founded in 2012 in small communities across Scotland with the aim of finding local solutions to flood risk, and provide information and training on a number of flood-related issues, including the use of flood adaptation measures. The flood action groups are self-relying and run by community members. Thus, if the existence of flood action groups is shown to influence adaptation behaviour, this may indicate an effective, low-cost and relatively simple way to promote private flood adaptation.

The remainder of the article is structured as follows. Section 5.3 reviews the theoretical framework and relevant literature. Section 5.4 describes the data and the statistical model. The results are presented in Section 5.5 followed by a discussion of the practical implications for encouraging households to implement private flood management measures and a conclusion in section 5.6.

5.3 Protection motivation theory and literature review

PMT (Rogers 1975; Rogers 1983) was originally developed for protective behaviour to health threats and has been successfully extended to other threats including natural hazards such as flooding.

The model distinguishes two cognitive steps to describe the decision process when individuals evaluate a threat and possible coping measures: 'threat appraisal' and 'coping appraisal'. The former includes perceived risk and fear and describes how threatened the individual feels by a specific danger. Coping appraisal focuses on possible responses to address the risk and can be divided into three components, 'response efficacy', 'self-efficacy' and 'response cost' (Rogers and Prentice-Dunn 1997). Response-efficacy expresses how effectively the individual perceives the measure to reduce risk. Self-efficacy describes whether the individual feels capable and confident to carry out the measure. Finally, response cost refers to both the financial as well as the emotional cost of implementing the measure. Taken together, coping appraisal and threat appraisal influence the protection motivation of an individual, which is considered as the variable to induce, sustain and direct the activity of the individual to protect themselves (Maddux and Rogers 1983). The responses can be both protective and non-protective.

Protective responses are those that reduce the threat and will be enacted if high risk perceptions coincide with a strong coping appraisal. The answers respondents give may be non-protective if high risk perceptions go together with low coping appraisals (Rippetoe and Rogers 1987). Non-protective answers include wishful thinking, avoidance and denial.

Several empirical studies support the applicability of PMT to flooding: Grothmann and Reusswig (2006) applied PMT to flood adaptation behaviour of private households in Germany showing a good fit in contrast to socio-economic variables. Bubeck et al. (2013) showed that coping appraisal is an important variable in terms of precautionary behaviour among flood-prone households along the river Rhine. In particular, response efficacy and self-efficacy contribute to the models of flood-adaptation behaviour. Similar results were found in other studies (Botzen et al. 2009; Botzen and van den Bergh 2012; Terpstra et al. 2009) confirming the importance of the coping appraisal for adaptation intentions. Zaalberg et al. (2009) carried out a comparative study between flood victims and non-victims in the Netherlands, showing that exposure positively affects protective motivation for future flooding. In addition to the PMT variables, a number of other factors may influence uptake. These include flood experience (Grothmann and Patt 2005; Kreibich et al. 2005; Siegrist and Gutscher 2006) as well as social networks such as neighbours or friends having implemented measures Bubeck et al. (2013), or public provision of flood risk adaptation measures inducing moral hazard (Le Dang 2014).

A number of studies conclude that risk communication for flooding and adaptation should focus on explaining the potential measures as well as on information on how to implement them (Bubeck et al. 2013; Clayton et al. 2015; Maidl and Buchecker 2014). While several studies have found that increased knowledge and information correlate positively with precautionary behaviour (Miceli et al. 2008; Thieken et al. 2006), numerous studies found no evidence of a direct effect of information sources and flood adaptation behaviour when risk perception was controlled for (Botzen et al. 2009; Grothmann and Reusswig 2006; Zaleskiewicz et al. 2002).

Behavioural decision research suggests that people may take action if they feel empowered to take charge rather than being treated as helpless citizens (Bush and Folger 1994; Page and Czuba 1999). Detailed, precise and personally relevant information might lead to more effective adaptation to flood risk (Klein 1998) such as proposing concrete action which can alleviate the problem. Such actions are likely portrayed as relatively easy, generating personal and social benefits (Moser 2010).

Tentative evidence has been found for earthquake preparedness through targeted information campaigns (Lindell and Perry 2000). Further, communication research recognises that messenger choice is critical in the communications process (Moser, 2010) and people are more likely to accept suggestions conveyed by people with similar views (Malka et al. 2009) and by peers as suggested by social learning theory (Bandura 1977).

We hypothesise that the activity of flood action groups works precisely through the mechanisms described above and can thus impact the motivation for implementing adaptation measures. The flood action groups provide information on a number of flood-related issues, including information and training on the use of flood adaptation measures, but also work as interest groups to lobby for flood protection schemes on the council level. They turn flooding into a local issue by creating responsibility and ownership to empower locals to take charge of their situation. In addition, flood action groups are locally grounded and people may thus be more likely to trust the recommended actions. Group members may influence neighbours and friends in the community and such social contacts have been shown to be influential in PMT studies (Bubeck et al 2013). Finally, the information is locally relevant and activity is on-going over a prolonged period.

The hypothesised mechanism within the PMT framework is presented in figure 5-1. The flood action groups may both affect the protection motivation directly but there may also be a mediating effect. The groups may positively impact self- and response-efficacy which in turn impact positively protection motivation. As far as we are aware, there is no research yet that explores specifically the effects of flood action groups on uptake of flood risk measures.

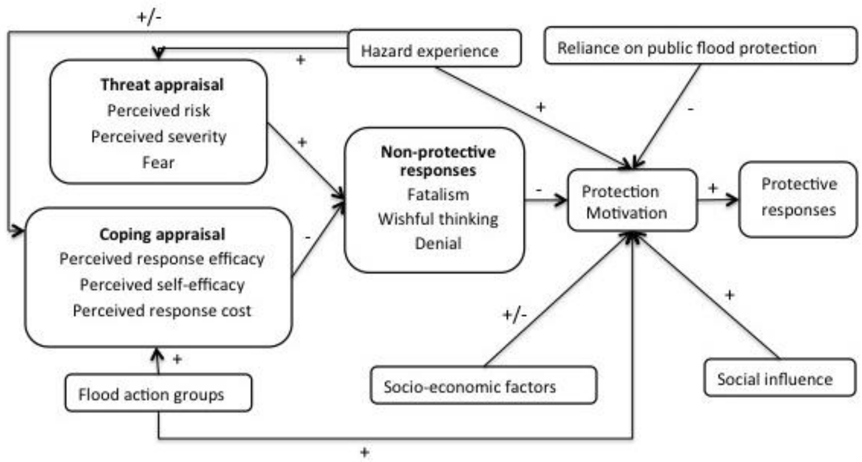

Figure 5-1 Conceptual framework for the data analysis (Adapted from Grothmann and Reusswig (2005))

The response variables within our analyses are household flood management measures. They include traditional measures, such as insurance and sandbags, but also more innovative and modern measures such as flood warnings and floodgates that have been specifically promoted or discussed by flood action groups.

Flood insurance reduces the financial consequences of a flood once it occurs and is identified in other studies as an adaptation measure (Bubeck et al. 2012b; Grothmann and Reusswig 2006). Sandbags can slow down the penetration of water through buildings by acting as a barrier. Floodgates for households are installed in the case of flooding to hold back floodwater and generally provide very effective protection from flooding (SFF, 2014). Flood warnings allow residents time to move valuable items to higher floors and to secure their properties with further measures.

In total 30 explanatory variables were gathered from the respondents, including their threat and coping appraisal, non-protective and protective responses, as well as socio-economic characteristics. Questions regarding financial aid by public authorities were included, which may provide a negative incentive to implement measures. Further, individuals may be influenced by neighbours and friends' adoption of measures (Ajzen 1991). Severity of experience of flooding in the near and distant past was also included as this has been observed to have positive effects on self-protective behaviour of natural hazards (Bubeck et al. 2012a). Finally, flood action group variables were included. Specifically, whether the respondents were aware of a flood action group in their community ('flood action group'), whether they were directly involved with the group ('involvement') as well as whether specific information was provided by the groups and whether the information was useful (See table 5-1 for the different types of information) (See table A1 in the appendix for a complete list).

5.4 Materials and Methods

Cross-sectional data from 124 private households across Scotland that have either experienced flooding or are at risk of flooding was gathered through a questionnaire-based survey and analysed with ordinal regression.

The questionnaire is based on the frameworks of Grothmann and Patt (2005) and Bubeck et al. (2013). It was refined with a pilot study of 18 flood risk households, and based on discussions with local flood groups and the Scottish Flood Forum (an NGO that deals both with flood prevention and post-flood assistance). The results from the pilot study were used to further develop the questionnaire structure. The survey was distributed online and in paper format to 600 residents in 34 communities across Scotland where flooding has occurred in the past and thus flood action groups were formed since 2012. The survey was also distributed at a flood exhibition in Scotland to include respondents from communities without a flood action group. In total 124 completed surveys were returned - a response rate of just over 20 %.

Table 5-1 shows a range of sample characteristics. All participants had experienced some flooding in the past and about 75% classified their flood experience as very severe. 85% of respondents have already implemented some form of flooding adaptation measure and 49% of participants confirmed they were actively involved in the community flood action groups. In the communities surveyed, the flood action groups provide information on the flood risk strategy of the local council (44%), flood warnings (66%), information on private flood management measures (56%) and, finally, information on how to use certain flood management measures (44%). The sample characteristics are not perfectly representative of the Scottish population. For example, average age and income in the study are higher than in the overall population. The percentage of people over 65 is above the Scottish average (39 per cent in the sample versus 17 per cent in the Scottish population (National Statistics 2014). However, over-representation of some population subgroups does not appear to affect estimates of means and proportions and is unlikely to affect correlation and regression analyses (Huang et al. 2012; Terpstra and Lindell 2013).

Variable	Percentage of total sample	Variable	Percentage of total sample
Age		**Flood experience**	
18-24	1	Yes	100
25-44	16	No	0
45-65	44		
65+	39	**Flood adaptation measure**	
		Yes	85
Gender		No	15
Female	51		
Male	49	**Flood action group**	
		Yes	84
Income		No	16
< £10,000	12		
£10,000-19,999	14	**Involvement in flood action group**	
£20,000-29,999	16	Yes	49
£30,000-39,999	10	No	51
£40,000-49,999	13		
£50,000-74,999	17	**Information through group on**	
£75,000-99,999	9	Flood risk strategy	44
> £100,000	9	Available measures	56
		Implementation of measures	44
Education		Flood warnings	66
Secondary education	29		
Diploma or vocational degree	22	**Usefulness of the information**	
Bachelor's degree	32	N/A	33
Master's degree	11	Not useful	6
Doctorate	6	2	8
		3	11
Ownership		4	16
Tenant	7	Very useful	27
Owner	93		

Table 5-1 Sample characteristics (n=124)

5.4.1 Statistical model

The response variables were measured on a five-point Likert-scale and are thus ordered and categorical. We estimate the effect of the potential determining factors on the different adaptation measures by using an ordered-logit model (Christensen 2015). We provide a polychloric correlation matrix in the appendix (table A3) for all dependent and independent variables which shows that the correlation between predictor variables included in the models is moderate (around 0.4). As the dataset is small and about 11 per cent of the data per variable are missing due to non-responses, we used multiple imputation to increase the ratio of observations to response variables to improve the efficiency of estimation. We applied the MICE package in R which uses Gibbs sampling to compute the missing values stochastically in a way that accounts for uncertainty (Honaker et al. 2015). We obtained five imputed datasets for our model selection. Despite the imputation, the observations to response variables ratio remains low, so backward selection is infeasible. For each of the response variables we therefore proceeded as follows: we entered each explanatory variable one at a time into an ordinal regression to determine which of the explanatory variables are significant at the 5 % level. We created the model that contains all of these variables, and then performed backwards selection on this model using the Wald-test (eliminating the least significant variables at each step, until all of the variables that remain within the model are significant at the 5 per cent level) to obtain our final ordered logit-model for each measure.

The estimated regression coefficients are on the scale of the cumulative log odds; we present the exponential of these coefficients, which correspond to the cumulative odds, because these have a natural interpretation. Thus, for instance, we compare people who use flood warnings to an average extent (3 on the Likert scale) or less with people who use flood warnings more.

5.4.2 Analytic methods

We ran three regressions per measure: 1. implementation of the household flood adaptation measures prior to the foundation of the flood action groups as the response variable, 2. implementation after the foundation of the flood action groups, 3. motivation for future implementation of measures. The latter two regressions included variables testing for the influence of the flood action groups to compare communities with and without flood action groups. For communities where flood action groups are in place, we tested for the influence of specific information provided by the groups.

To test our hypotheses on the effects of the flood action groups, we also ran a mediation analysis based on the standard approach of Baron and Kenny (1986) to explore whether the flood action groups variables may be correlated with the two components of the coping appraisal which in turn may be correlated with the measure uptake as hypothesised in figure 5-1. That is, we clarified the degree of correlation between the different variables in a relationship of X > Y > Z, where X refers to the flood action related variables, Y describes self- and response efficacy for the different measures and Z the response variables. To test for partial and complete mediation, we verify whether there are significant relationships in regression equations between X and Y (with Y being the outcome) and X and Z (with Z being the outcome). Additionally, we test whether adding X in the regression equation of Z on Y statistically significantly improves the model by using Wald tests to show partial mediation. If we find no added significance, this suggests complete mediation, i.e. the mediator 'absorbs' the effect of the flood action variables. We also test for mediation of flood experience through threat and coping appraisal as hypothesised in figure 5-1. The cross-sectional nature of the data inhibits inferring causal effects, therefore the results should be considered as a clarification of degrees of correlations between the variables (Lindell and Hwang 2008). We provide McKelvey Zavoina R^2 as goodness-of-fit measures.

5.5 Results and discussion

Section 5.5.1 interprets the regression models for the four types of flood adaptation measures as well as the variables influencing response-efficacy and self-efficacy. Section 5.5.2 provides a short discussion.

5.5.1 Results

Table 5-2 presents the results of the regression equations for the four household flood management measures. Across the four measures, more explanatory variables fitted to data from respondents were identified for the more recent uptake of flood risk management measures as well as for intentions in the near future rather than for the uptake prior to 2012.

This makes sense for two reasons. First, people may not remember the exact extent of their use of, for instance, sandbags prior to 2012, and it may have varied over the time period. Second, the dataset is cross-sectional apart from the response variables. The respondents' perception may have changed over time but also their socio-economic status, so we find a better fit regarding their current opinions/status, which is reflected in current uptake and intentions for future uptake in the present. The cross-sectional nature of data also implies that the relationships should be interpreted as correlation rather than causation.

All communities					**Communities with a flood action group**			
FLOOD WARNINGs		Log (odds ratio)	Odds ratio	McKelvey Zavoina R2		Log (odds ratio)	Odds ratio	McKelvey Zavoina R2
	A1							
	Pre-2012 uptake							
Threat appraisal								
Coping appraisal								
Flood action group variables								
Other variables								
	A2				**A4**			
	Post-2012 uptake			0.38	Post-2012 update			0.32
Threat appraisal								
Coping appraisal	Self-efficacy	0.65 (0.13)	1.9**		Self-efficacy	0.84 (0.16)	2.3**	
	Response cost	-0.35(0.14)	0.7*					
Flood action group variables								
Other variables	Neighbours	0.28 (0.12)	1.3*					
	A3				**A5**			
	Intended uptake			0.37	Intended uptake			
Threat appraisal	Risk	0.46 (0.15)	1.6***					0.50
Coping appraisal	Self-efficacy	0.79 (0.14)	2.2***		Self-efficacy	0.53 (0.19)	1.7*	
					Response-efficacy	0.58 (0.22)	1.8*	
Flood action group variables					Information on flood warnings	1.26 (0.54)	3.5*	
					Information on flood risk strategy	1.16 (0.44)	3.2*	
Other variables								

Table 5-2 Variables associated with the pre-2012, post 2012 and intended uptake of flood warnings (A1-A5), sandbags (B1-B5), flood gates (C1-C5) and insurance (D1-D5), for all communities and for communities with a flood action group; Signif. codes: 0.001 '*' 0.01 '**' 0.05 '*'; standard errors in parentheses**

All communities					Communities with a flood action group			
SANDBAGS		Log (odds ratio)	Odds ratio	McKelvey Zavoina R2		Log (odds ratio)	Odds ratio	McKelvey Zavoina R2
	B1							
	Pre-2012 uptake							
Threat appraisal								
Coping appraisal								
Flood action group variables								
Other variables								
	B2				**B4**			
	Post-2012 uptake			0.22	Post-2012 uptake			0.28
Threat appraisal	Risk	0.62 (0.15)	1.9***		Risk	0.71 (0.18)	2***	
Coping appraisal	Self-efficacy	0.39 (0.13)	1.5***		Self-efficacy	0.56 (0.16)	1.8***	
Flood action group variables								
Other variables								
	B3				**B5**			
	Intended uptake			0.20	Intended uptake			0.20
Threat appraisal	Risk	0.57 (0.14)	1.8***		Risk	0.6 (0.17)	1.8***	
Coping appraisal	Self-efficacy	0.37 (0.13)	1.4***		Self-efficacy	0.43 (0.16)	1.5***	
Flood action group variables								
Other variables								

Table 5-2 continued

All communities					Communities with a flood action group			
FLOOD GATES		Log (odds ratio)	Odds ratio	McKelvey Zavoina R2		Log (odds ratio)	Odds ratio	McKelvey Zavoina R2
	C1							
	Pre-2012 uptake							
Threat appraisal								
Coping appraisal								
Flood action group variables								
Other variables								
	C2				**C4**			
	Post-2012 uptake			0.13	Post-2012 uptake			0.17
Threat appraisal					Risk	0.4 (0.18)	1.5*	
Coping appraisal	Self-efficacy	0.38 (0.13)	1.5**					
Flood action group variables					Information on implementation	1.29 (0.41)	3.6**	
Other variables	Implementation with neighbours	0.78 (0.35)	2.2*					
	C3				**C5**			
	Intended uptake			0.33	Intended uptake			0.44
Threat appraisal	Risk	0.64 (0.16)	1.9***		Risk	0.73 (0.20)	2.1***	
Coping appraisal	Self-efficacy	0.60 (0.13)	1.8***		Self-efficacy	0.73 (0.17)	2.1***	
Flood action group variables					Neighbours	0.4 (0.15)	1.5***	
Other variables								

Table 5-2 continued

All communities					Communities with a flood action group			
INSURANCE		Log (odds ratio)	Odds ratio	McKelvey Zavoina R2		Log (odds ratio)	Odds ratio	McKelvey Zavoina R2
	D1							
	Pre-2012 uptake			0.10				
Threat appraisal								
Coping appraisal	Self-efficacy	0.27 (0.12)	1.31*					
Flood action group variables								
Other variables	Neighbours	0.27 (0.12)	1.31*					
	D2				**D4**			
	Post-2012 uptake			0.12	Post-2012 uptake			0.19
Threat appraisal								
Coping appraisal								
Flood action group variables								
Other variables	Ownership	2.41 (0.71)	1.1**		Ownership	2.29 (0.85)	9.9**	
					Overall flood experience	-0.73 (0.35)	0.48*	
	D3				**D5**			
	Intended uptake			0.14	Intended uptake			0.15
Threat appraisal								
Coping appraisal	Response efficacy	0.32 (0.13)	1.4*		Response efficacy	0.36 (0.15)	1.4*	
Flood action group variables					Information on available measures	1.16 (0.44)	3.2*	
Other variables	Ownership	1.96 (0.64)	7.1**					

Table 5-2 continued

5.5.1.1 Coping appraisal

Self-efficacy is significant within at least one of the analyses for each measure. Response efficacy is significant for the use of insurance (D3 and D5) and flood warnings (A5). This confirms findings of other studies (Bubeck et al. 2013; Grothmann and Patt 2005; Zaalberg et al. 2009) showing that the belief in the effectiveness of a measure and the level of confidence to implement the measure play a central role in the uptake of household flood management measures. It should be noted that there are possible behavioural feedback mechanisms for the two variables, which we cannot detect due to the cross-sectional nature of the data. Having already implemented measures might increase people's confidence (self-efficacy) and to justify the implementation rationally (Festinger 1957), people are likely to assume the effectiveness of the measure (response-efficacy) (Grothmann and Reusswig 2006). Thus, we cannot infer whether response and self-efficacy lead to protective behaviour or vice versa. However, two arguments may indicate the former: first, for future intended (increased and new) uptake the relationship is more likely to move from self-efficacy to protective behaviour (unless the intention to undertake a measure already leads to increased confidence and belief in effectiveness), and second, some experiments in the context of PMT have indicated the former as well (Flynn et al. 1995).

The third variable of coping appraisal, response cost appears to be mostly non-significant. An exception is the cost for flood warnings with a negative coefficient for intended uptake (A5) indicating a lower use with higher cost. This is a surprising result for a low cost measure such as flood warnings. This might reflect the cost of accessing flood warnings, mostly provided through text messages or the internet, which could be more challenging for the mostly older respondents of the survey. Receiving financial support is not significant in the regressions. The lack of significance of response cost and financial support highlight that cost is not decisive when it comes to encouraging the uptake of less expensive adaptation measures confirming the findings of Terpstra and Lindell (2013). This may be different for more costly structural measures as found by other studies (Grothmann and Reusswig 2006; Poussin et al. 2014). While it is surprising that cost does not have a negative effect on insurance, conversations with the flood action groups indicated that all households are keen to obtain flood insurance (if provided by the insurance company) despite the high cost.

5.5.1.2 Threat appraisal

Risk perception, a component of threat appraisal, is significant for a number of the analyses. Some studies have found a minor contribution of risk perception (Bubeck et al. 2013; Koerth et al. 2013) while others observe a strong link between increased risk perception and increased uptake of measures (Bichard and Kazmierczak 2012; Miceli et al. 2008; Osberghaus 2015). Due to the different formulation of risk it is challenging to compare the results across studies. A feedback mechanism, similar to that for coping appraisal may exist, such that risk perception may decrease after implementation of measures (Weinstein et al. 1998). However, we cannot necessarily observe risk to be significant for intended uptake where a feedback mechanism is less likely (unless the intent of uptake alone reduces risk perception). Rather, we find significance for risk in particular for floodgates (C3-C5) and sandbags (B2-B5). This high and significant risk perception for these two measures may be related to the fact that they represent physical actions to avoid homes being flooded; where respondents' decisions to implement these emergency measures reveal their perception that the risk is real and high. The results indicate that high risk perception may lead to increased flood preparedness but appears to depend on the measure. We do not find significance for fear as the second component of threat appraisal which may be implicitly measured by risk.

5.5.1.3 Social environment, previous flood experience, socio-economic variables, non-protective answers

We note the significance of neighbours in the use of insurance (D1), flood warnings (A2), floodgates (C2 and C4), as in other studies confirming the importance of the influence of peer behaviour (Bubeck et al. 2012b; Bubeck et al. 2013). For the use of floodgates post-2012 (C2), we find significance for the variable 'implementation with neighbour'. This likely reflects that non- or semi-detached houses require joint measures such as floodgates to protect the homes. Therefore, a respondent who has implemented a measure together with their neighbour is more likely to have set up a more sizeable floodgate.

Flood experience has only been found to be significant for the post-2012 insurance regression (D4) with a negative coefficient. The negative coefficients of flood experience is counter-intuitive, but other studies have found similar results (Bubeck et al. 2013; Kreibich et al. 2011b) and have been linked to higher insurance premiums due to an increased of risk to flooding. The lack of significance of flood experience may be explained by a complete mediation of experience on uptake through threat and coping appraisal (Bubeck et al. 2013) as indicated in figure 5-1. In our mediation analysis (see table 5-3), we find complete mediation effects for flood experience variables, for example for flood gates and sandbags through both threat and coping appraisal and for flood warnings for the latter. The figures provided in the table specify the p-values for the equations on top of the columns testing their significance as described in section 5.4.2. (For a complete list of the mediation results see table A4 in the appendix.).

In line with other studies (Bubeck et al. 2013; Grothmann and Reusswig 2006; Osberghaus 2015; Zaalberg et al. 2009), socio-economic variables explain relatively little of the data. Here, we only find that ownership positively influences the uptake of insurance (D2-D5) which is not surprising given that owners are responsible for their own property. Finally, we found no significance for non-protective responses once controlling for other variables.

	Dataset and variables tested for mediation	Response variable	Mediator	Explanatory variable	Z = bX	Z = aY + bX vs. Z = bX	Z = aY + bX vs. Z = aY	Y = bX
		Z	Y	X				
FLOOD GATES								
E1 Partial mediation	FLOOD ACTION GROUP VARIABLES							
	Communities with a flood action group	Intended uptake	Response efficacy	Usefulness	0.007	0.033	0.045	0.049
			Self-efficacy	Information on available measures	0.002	0.006	0.037	0.007
	FLOOD EXPERIENCE VARIABLES							
	All communities	Intended uptake	Self-efficacy	Post-2012 flood experience	0.015	0.003	0.035	0.035
			Threat	Post-2012 flood experience	0.015	0.038	0.035	0.000
			Threat	Average flood experience	0.009	0.025	0.040	0.000
	FLOOD ACTION GROUP VARIABLES							
	Communities with a flood action group	Intended uptake	Self-efficacy	Information on implementation	0.020	0.002	0.177	0.001
			Response efficacy	Information on implementation	0.020	0.036	0.090	0.000
	FLOOD EXPERIENCE VARIABLES							
	All communities	Post-2012 uptake	Response efficacy	Pre-2012 flood experience	0.185	0.035	0.429	0.032
		Intended uptake	Risk	Post-2012 flood experience	0.015	0.002	0.143	0.000
			Risk	Average flood experience	0.009	0.001	0.171	0.000
			Response efficacy	Post-2012 flood experience	0.015	0.003	0.035	0.035

Table 5-3 Significance of the results of the mediation analysis for mediation of flood experience variables and flood action group variables through coping and threat appraisal. The figures provided in the table specify the p-values for the equations on top of the columns testing their significance.

	Dataset and variables tested for mediation	Response variable	Mediator	Explanatory variable	Z = bX	Z = aY + bX vs. Z = bX	Z = aY + bX vs. Z = aY	Y = bX
		Z	Y	X				
SANDBAGS	FLOOD EXPERIENCE VARIABLES							
	All communities	Post-2012 uptake	Risk	Post-2012 flood experience	0.040	0.002	0.520	0.000
			Risk	Average flood experience	0.022	0.002	0.376	0.000
FLOOD WARNINGS	FLOOD ACTION GROUP VARIABLES							
	Communities with a flood action group	Post-2012 uptake	Self-efficacy	Usefulness	0.021	0.008	0.212	0.014
			Response efficacy	Usefulness	0.021	0.005	0.244	0.004
		Intended uptake	Self-efficacy	Usefulness	0.009	0.001	0.199	0.014
			Response efficacy	Usefulness	0.009	0.000	0.173	0.004
		Post-2012 uptake	Self-efficacy	Information on implementation	0.078	0.002	0.892	0.005
		Intended uptake	Self-efficacy	Information on implementation	0.046	0.000	0.641	0.005
			Response efficacy	Information on implementation	0.046	0.000	0.191	0.028
			Self-efficacy	Information on available measures	0.012	0.001	0.541	0.004
			Response efficacy	Information on available measures	0.012	0.000	0.117	0.031
		Post-2012 uptake	Self-efficacy	Information on flood warnings	0.001	0.008	0.123	0.000
		Intended uptake	Self-efficacy	Information on flood warnings	0.001	0.003	0.202	0.000
	All communities	Post-2012 uptake	Self-efficacy	Existing schemes	0.012	0.001	0.551	0.000
			Response efficacy	Existing schemes	0.012	0.001	0.228	0.000
		Intended uptake	Self-efficacy	Existing schemes	0.022	0.000	0.325	0.000
			Response efficacy	Existing schemes	0.022	0.005	0.199	0.000

Table 5-3 continued

5.5.1.4 FLOOD ACTION GROUPS

We find a positive relationship where flood action group variables contribute significantly to the explanation of the data, indicating that such groups may positively influence the uptake of household flood management measures. Yet, significance was established only in a few regressions (A5, C4, C5, D5). We find no link for sandbags. This may reflect that sandbags are long-standing household flood adaptation measures and the promotion by the flood action groups cannot make a significant contribution to their increased uptake. Indeed, about 60 % of respondents already used sandbags in both samples before 2012. Generally, we do not find a link between the presence of a flood action group in a community and not having one and uptake. The significant correlations are for variables which represent specifically provided information by the flood action groups.

We can speculate about the direction of - due to the cross-sectional data - the effect for insurance: the variable 'having obtained information on available measures' is significant for the intended uptake of insurance for communities with a flood group present. This may reflect that people who are at risk of flooding and have an expensive insurance premium, or even struggle to obtain insurance, are more likely to obtain further information through the flood action groups. This was confirmed by talking to the flood action groups. The members aim to find other solutions to flood risk beyond insurance and indeed we find significant correlations between insurance and the other measures of between 0.18 and 0.46. If these measures were substitutes, the correlations would be negative. These findings have been confirmed by other studies (Hudson et al. 2015; Lindell et al. 2009; Lindell and Hwang 2008). However, there may also be an exchange in the groups regarding the most appropriate insurance cover, which was also confirmed by the groups themselves, which may result in a more comprehensive cover for members.

For floodgates, we find the size of the positive effect to be of factor 3.6 for post-2012 uptake if respondents received information on how to implement specific measures. The flood action group members confirmed in personal conversation that the setting up of floodgates was discussed and demonstrated as part of the flood action group activities.

For flood warnings, we find an increased likelihood of intended uptake of factor 3.5 if information on flood warnings was provided by the flood action group, highlighting the importance of specific information as for floodgates. Similarly, if respondents have received information about the flood risk strategy of their council, they have a higher likelihood of using flood warnings in the future. We can speculate whether this is due to local authorities recommending the use of flood warnings or the insight of the respondents that structural flood risk schemes may take considerable time to materialise.

In addition to significant correlations between flood action variables and measures, we also find mediating effects of self-efficacy and response efficacy with respect to flood gates and flood warnings as hypothesised in figure 5-1 (see table 5-3 for significant effects and table A4 for all analyses). We find both partial and complete mediation for the intended uptake of flood gates such as flood action variables impact positively whether a respondent perceives gates as effective and is confident to use it. This highlights that such information may encourage protection motivation going forward as the respondents plan to implement and use the flood gates in the nearby future. Specifically, if the obtained information from the group is perceived as useful, when information on available measures has been provided, there is a mediating effect. The number of significant mediating relationships is more extensive for flood warnings and applies to both post-2012 and intended uptake of flood warnings. The same variables as for flood gates are significant but in addition also whether information on flood warnings have been provided and information on how to implement measures.

There is also complete mediating effect of, 'existing schemes' for the use of flood warnings for the whole sample for post-2012 and intended uptake. Existing schemes refer to assistance (including that from flood action groups but also from the local council) with household flood management measures. While we cannot pin down the exact mechanism of 'existing schemes' on response and self-efficacy, we can deduce that specific help and information for flood risk at the household level appear to have a positive effect.

5.5.2 Discussion

The potential of capitalising on community networks to assist in the operation of appropriate flood response strategies and their importance in building trust between locals and professionals has been recognised (Richardson et al. 2003), and our work tentatively confirms this hypothesis.

The fitted models indicated a positive effect on uptake for insurance, floodgates and for flood warnings. It appears that having a flood action group in the community, or being involved in one, does not necessarily lead to an increased uptake of measures as the variable 'flood action group' and 'involvement' did not prove significant. It is rather when the groups provide tailored information such as on flood warnings or how to implement measures that significant correlations were observed, confirming findings from studies on adaptation communication as described in the literature review.

We also find partial and complete mediating effects through the correlation of the flood action groups with increased self-efficacy and response-efficacy which are in turn associated with uptake and appear key in the uptake of precautionary measures, as can be seen in our regressions and in other studies using PMT as theoretical framework as shown in figure 5-1. We have therefore confirmed that coping appraisal is related to hazard adjustment but also carried out an investigation into how it may potentially be influenced. Again, we found effects for flood gates and flood warnings, if specific information had been provided which is also subsumed in the significance of whether the obtained information is perceived as useful.

The UK government encourages autonomous adaptation to climate change, with flooding being one of the major expected climate change impacts in the UK (DEFRA 2013b). Thus, such groups can prove to be a cost-effective way of reaching the given aim of increasing household resilience to flooding as well as discussing climate change as a wider encompassing issue. If the flood action groups can be 'kick-started' with the help and direction of the council and appropriate NGO's[15] their subsequent running will be ensured by the community itself, relying on active and engaged community members. This is the case with the observed groups in the study where the support of the local councils was limited to providing sandbags to be stored in the communities. While we do not have

[15] The flood action groups in Scotland considered in the survey have been set up with the support of the Scottish Flood Forum, a NGO that aims to support communities that are at risk of flooding.

estimates of the costs of running flood action groups, we know that household flood management measures often exhibit high benefit-cost ratios (Holub and Fuchs 2008; Kreibich et al. 2011a), and would therefore expect its cost to be below that of a structural measure for the same benefit. Indeed, flood protection on the household level and supported by the community may prove to be the only viable solution for many small communities where larger structural flood defence measures will not pass a cost-benefit test due to a too small population.

A number of caveats need to be considered. First, the sample (n=124) is very small, which sets a limit to the complexity of the model and the robustness of the inference. This highlights the importance of conducting research on a larger scale to confirm the results of the study and to obtain more precise estimates. Second, a different item to describe 'real' risk perception may have been feasible and delivered different results. This includes, amongst others, dread and unknown risk (Fischhoff et al. 1978), combining these with well known disaster risks (Lindell 1994; Trumbo et al. 2016) or people's expectations of the personal impacts caused by a disaster (Huang et al. 2012; Mileti and Peek 2000; Mileti and Sorensen 1987). Third, the changes in uptake of certain measures may also partly be due to external reasons not captured in the study, such as easier access to flood warnings or the challenge of obtaining flood insurance for certain high risk properties.

5.6 Conclusion

This study examined the factors influencing the uptake of four household flood adaptation measures in small communities around Scotland using a cross-sectional survey (n=124) within an extended framework of PMT. The main focus was on testing whether local flood action groups, in which residents promote the deployment of flood management measures, have a positive effect on uptake. The fitted models indicated a positive effect for the use of insurance and of floodgates if information on measures and implementation were provided; for flood warnings we detected a link if specific information on flood warnings were provided. Additionally, we found a mediating effect for flood warnings and floodgates. The flood action group variables appear to positively impact the coping appraisal variables which are key for protection motivation. The conclusion that follows from Chapter 5 is that flood action groups may increase the uptake of precautionary measures in particular by providing information about specific measures. This highlights the importance of bottom-up adaptation to climate change for flooding given limited resources of local authorities such that top down adaptation – whether robust or not may not occur. The promotion of well-designed flood action groups at the policy level can provide a cost-effective way of increasing household resilience to flooding in Scotland and elsewhere.

6 Conclusion

6.1 Contribution of the research

Since the work on this dissertation began at the end of 2012, the adaptation agenda has been advanced by cities, regions and countries to develop much needed climate change adaptation plans to counteract potentially severe climate change impacts. This includes for example, adaptation plans by cities such as New York, US, London, UK, Quito, Ecuador, national adaption plans such as the UK National Adaptation Programme (DEFRA 2013b), or the further development of national adaptation programmes of actions (NAPA) by the least developed countries under the UNFCCC and many others.

In many cases, those documents are so far statements of intent identifying vulnerable sectors where action is required. Planning, implementing and monitoring of the necessary adaptation action are the next steps.

This dissertation contributes to these tasks ahead in particular to planning and to an extent to implementation due to its focus on enhancing decision-making for climate change adaptation and providing applied guidance in this field. The work presented is grounded in the economic principle of allocating scarce resources in an efficient manner, where the greatest marginal benefits can be obtained relative to marginal costs.

Chapters 2 through to 5 have provided insights and applications[16] for economic appraisal under climate change uncertainty. Taken as a whole, these chapters have demonstrated different tools available to decision-makers when appraising adaptation options. Chapter 2 highlighted the shortcomings of standard decision-making tools that do not consider uncertainty. It focuses on the importance of moving decision-makers away from striving for solutions that assume an investment today will necessarily match the actual state in the future. Instead, robust decision-making tools under uncertainty may be more appropriate under climate change uncertainty and the choice of the robust tool under uncertainty will

[16] The analysis of chapter 4 for example is used by public authorities to help understanding the economic implications of the projects of the Tweed Forum in the Eddleston Water Catchment in the Scottish Borders.

depend on the characteristics of the adaptation project. This was illustrated through a flow chart. However, robust decision-making tools under uncertainty are no panacea either. They provide performance across a range of climate change scenarios, but they may yield lower overall performance if compared with the alternative strategy under the actual climate outturn, i.e. they may not allocate resources as efficiently as the optimal strategy which would have been chosen if no climate change uncertainty existed.

Furthermore, the applicability of and the need for robust decision-making tools under uncertainty may depend on the sector being considered, as Chapter 3 demonstrates. While agriculture is highly vulnerable to climate change, many of the impacts can be counteracted through managerial changes after the climate change signal has occurred. Those decisions are then based on farmers making informal assessments of the costs and benefits of the options. Nevertheless, there is a role for robust decision-making in agriculture, in particular for complex tasks on a regional level (e.g. water supply) and with respect to the increased weather variability that farmers may have to confront with climate change.

All chapters on decision-making under uncertainty highlighted that (most) robust decision-making tools under uncertainty are resource-intense and decision makers need to balance the resources required for employing the methods with the added value they can offer. A scenario-based analysis as presented in Chapter 4 will provide information on the level of protection a specific measure can provide under different climate change scenarios (in addition to other ecosystem services) and allows the decision-maker to understand the implications of their investment under alternative futures. A ROA as carried out in Chapter 5 enhances such information by integrating uncertainty in the decision-making process such that the decision-maker can adjust the strategy over time and allocate the resources more efficiently. A ROA that would provide a complete CBA would offer even more information (as suggested in the further research avenues), and the complexity of the analysis could be extended further. Some decision-makers will have the resources to carry out more resource intense appraisals than others. Thus, one of the main conclusions that emerges from Chapters 2 to 5 is the importance of acknowledging the climate change uncertainty and integrating it in economic appraisal by first making an informed decision about the choice of tool to eventually allow for better adaptation decision-making.

Chapters 2 to 5 assume a top-down perspective for the most part with a public decision-maker (apart from the farm-level options). Indeed, in many cases, adaptation tasks will fall into the realm of a public decision-maker due to the sectors affected (e.g. public buildings and road infrastructure, health). However, developing and fostering bottom-up tools are essential to complement the top-down approach. A top-down approach will not always be implemented, given the political cycle which results in decision-making with a five-year perspective when appropriate adaptation action might require planning for much longer times. In addition, many adaptation tasks will affect only few households (such as for flood infrastructure) and public intervention is not viable as the assets at risk may not be sufficiently valuable.

Bottom-up approaches start out with the households and applications may be found in many different fields. Chapter 6 asserts that household flood risk adaptation may be potentially economically efficient to achieve flood protection. Public flood infrastructure would likely not pass the cost-benefit test in many of the areas studied while household flood protection measures can have benefit-cost ratios above 1. In addition, re-instatement costs of repairing housing after flooding will be lower with appropriate household flood protection measures which reduce the flood impact.

The main message that emerges from Chapter 6, however, is the importance of empowering vulnerable households and groups to tackle the adaptation challenge. In many cases the threats from climate change impacts, such as more frequent flooding in the future, may cause feelings of helplessness. Instead, if people are aware of effective counter measures (such as flood gates or similar) and feel confident about implementing them, they are more likely to take on the task of preparing for changes in flood frequency.

The initiative for flood action groups began within communities (and with the help of a NGO) and Chapter 6 elicited the mechanisms through which those groups may work, which appear to be effective. It seems that tailored information, including training for using specific measures, can make a difference. Thus, if a public authority can develop a toolkit for local groups which includes advice on how to set up a successful local flood action group and what activities to carry out and can successfully initiate its functioning, the vulnerability of the community at risk will be reduced and successful bottom-up adaptation is feasible.

The applications of Chapters 4 to 6 deal with flooding as a potential climate change impact. Extreme weather events including flooding, which can in an increasing number of cases be linked to climate change through attribution studies, receive a lot of attention by the general public given the immense economic damage and significant impacts on many people's lives. Adapting to flooding with flood risk infrastructure or household flood protection is one straightforward option and the robust decision-making tools under uncertainty discussed are very well suited to appraise flood infrastructure given their long life times where climate change uncertainty plays a major role. However, decisions about flood risk infrastructure are often driven by other factors than economic ones. Political pressure may result in building flood risk infrastructure which may not necessarily have passed a standard CBA (Helm 2016). Also, flood risk infrastructure may solve flooding in one place and aggravate it another (Iacob et al. 2014). Flooding is a serious climate change threat and decisions on how to prevent or deal with it must be taken with caution.

Carrying out an economic appraisal of a flood infrastructure and integrating uncertainty should be one important objective but a more comprehensive adaptation strategy would likely consider flood risk management at the catchment scale to understand better how the different drivers of flood risk (in particular land use) interact. NFM is also one component towards catchment flood management with the aim of re-naturalising flows. We have shown the potential of NFM with respect to afforestation. The measure showed very high positive net NPV but this was driven by eco-system services other than flood risk regulation as shown in Chapter 4. Chapter 5 showed that least-cost strategy in the context of a 1 in 20 year return period event would be to allow flooding rather than a large investment in afforestation. The selection of the least cost strategy under a 1/20 year event would result in flood damage rather than a large investment in afforestation. Both results suggest that afforestation (in the case study area) can constitute an important component of an economically efficient flood risk reduction but likely not to the degree that it prevents a flood of the 1/20 year event under climate change. Indeed, it may be the case in the future with further climate change that the most economically efficient option for some areas (including for our case study) will be to allow for flooding in low frequency flood events.

6.2 Limitations of the research

A dissertation is naturally limited by the chosen scope of the studied field. Here, the robust-decision-making methods discussed may not comprehensively describe the continuously evolving body of such tools. Furthermore, robust decision-making tools under uncertainty may have different implications in sectors other than agriculture, for example in the energy sector with many long-lived infrastructures. In addition, the presented work was written in a European context. Many of the implications may not hold for developing countries which are particularly vulnerable to climate change but are without the institutional resources of Europe. Subsistence farmers may not be able to adopt the presented options due to limited resources; flood action groups are unlikely to be formed in a developing context and the data to carry out an economic appraisal with robust decision-making methods under uncertainty may not be available in many places.

Each of the applied Chapters 4-6 has limitations with respect to their research designs which are described in the chapters themselves. Possibly, the greatest limitation of chapters 4 and 5 on decision-making under uncertainty is the 'remaining' uncertainty (of different types). The estimates for the low, central and high scenario in Chapter 4 show a wide disparity, in particular due to the uncertainty of the benefits of ecosystem services which makes it difficult to obtain a good understanding of the magnitude of the benefits. Chapter 5 provides probabilities for different climate change paths which may not be possible yet. Nevertheless, the results of both chapters allow for a better understanding of the direction of change, if not necessarily the precise magnitude of the change. Chapter 6 is the first study (as far as is known) on the impact of flood action groups on the uptake of flood management measures and all results are correlations rather than cause and effect due to the cross-sectional data. Thus, one should be cautious in deducing strong implications from the results without further research.

Climate change adaptation is closely related with climate change mitigation. The more mitigation will be undertaken in the near future, the less adaptation may be needed and vice versa. While mitigation was indirectly inferred in Chapters 4 and 5 by choosing a medium scenario for mitigation to obtain climate projections, it was not explicitly included in the modelling. This is partly due to the different scales at which adaptation and mitigation happen, as mitigating locally will not have the same impact as adapting locally, but the added uncertainty should be taken into account.

These limitations also provide input for potential further research avenues, several of which are described below.

6.3 Future research avenues identified

On the macro-level:

- The choice of the discount rate:

  This thesis applied the discount rate provided by the UK government for policy making but the choice of the discount rate remains controversial (i.e. the social vs. the private discount rate) and has a profound impact on the outcome of studies (Williams 2012).

- The integration of attitudes to risk in decision-making for adaptation:

  Chapters 2, 3, and 5 touched briefly upon attitudes to risk in decision-making, which can play an important role when the value at risk is high such as for farmers facing increased weather variability or for flood management and the implications could be explicitly modelled.

On the sector and micro level:

- The role of equity in the context of flood risk management for climate change adaptation.

  Chapter 6 highlights the potential of empowering citizens to engage in climate change adaptation. The groups analysed in Scotland engage in household flood protection but also lobby with the local council for their interests. This should be an inclusive process that represents the interests of the whole local community in particular as poorer households tend to be more vulnerable to flooding (Lindley et al. 2011). Thus, a further analysis could examine the socio-economic background of the groups and how to (potentially) include further socio-economic groups.

- Who pays for flood risk infrastructure?

  Chapters 5 and 6 assumed a public decision-maker that pays to put in place and maintain the flood infrastructure, but this may not necessarily be the equitable answer. If a public authority decides to invest in flood infrastructure, there is an argument for households that directly benefit from the flood protection to contribute to its cost. Currently, all tax payers pay for flood infrastructure in the UK without necessarily benefiting from it. Indeed, the current set-up encourages moral hazard to an extent as households may not be necessarily discouraged from moving to areas at flood risk if they believe that they can rely on public flood protection. The design of costing flood risk infrastructure is an important topic given that we may expect its cost to increase further with climate change.

- Other drivers of flood risk

  Climate change is one driver of changing flood risk but others, notably land-use, also exist. Strategies to lower the exposure to flood risk include for example regulating the building on flood plains, decreasing impermeable surfaces and considering agricultural land-use (Ball and Green 2007). The former is strongly influenced by local development plans and the latter by agricultural policy such as the European Common Agricultural Policy (CAP). A comprehensive climate change adaptation strategy for flood risk needs to explicitly consider the impact of land-use policy and be designed accordingly.

- Optimising for ecosystem services and flood risk benefit when analysing NFM.

  Chapter 5 and 6 use cost-benefit analysis and life-cycle cost strategy to analyse respectively the investment question for NFM. A potential next step could be a) a complete CBA (which necessitates a damage function) which aims to minimise total cost (of flooding and investment in the measure) and b) to maximise for ecosystem services at the same time to obtain trade-offs.

Many advances have been made in the scientific field of climate change adaptation in the past decade but more questions have also emerged. This dissertation has contributed to the scientific work on decision-making for climate change adaptation with a focus on applied work mostly in the context in the flooding. Given the immense challenges associated with climate change, with increased frequency of flood events being just one of them, it is the task of the scientific community (including the author of this dissertation) to ensure that the evidence that emerges from the field of climate change adaptation is continually communicated to support decision-makers. This is critical for adaptation to be planned and implemented by individual households and policy makers on local, regional, national and international levels.

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7 Appendix

Explanatory variable	Description	Coding
Gender	Respondent's gender	1= female, 0 = male
Education	Respondent's highest level of completed education	1= secondary education, 2= diploma or vocational degree, 3= bachelor's degree, 4 = master's degree, 5= doctorate
Ownership	Ownership of the home the respondent lives in	1=yes, 0=no
Age	Age categories	1=18-24, 2=25-44, 3=45-65, 4=65+
Income	Yearly income after tax of the respondent	1= < £10,000, 2= £10,000-19,999, 3=£30,000-39,999, 4 = £40,000-49,999, 5 = £50,000-74,999, 6 = £75,000-99,999, 7 = > £100,000
Self-employment	Employment status of respondents	1=yes, 2=no
Flood experience pre-2012	Flood experience until 2012	1= no flooding at all, 2, 3, 4, 5= very severe flooding
Flood experience post-2012	Flood experience since 2012	1= no flooding at all, 2, 3, 4, 5= very severe flooding
Overall flood experience[1]	Overall flood experience	1= no flooding at all, 2, 3, 4, 5= very severe flooding
Average flood experience[2]	Average flood experience	1= no flooding at all; 2; 3; 4; 5=very severe flooding
Threat	Perceived severity of flooding in the respondent's home in the next 20 years	1=not severe at all, 2,3,4,5=very severe
Risk	Perceived risk of a harmful flood event occurring at the household	1=not likely at all; 2; 3; 4; 5 = very likely
Fear	Perceived worry that a harmful flood event occurs at the household	1=not at all, 2, 3, 4, 5= to a great extent
Fatalism	To what extent do you agree with the following statement: "I believe flooding will happen from time to time and we have to accept its consequences"	1= strongly disagree, 2= disagree, 3= neither agree nor disagree, 4= agree, 5= strongly agree, don't know= blank
Avoidance	To what extent do you agree with the following statement: "I try not to think about the possibility of flooding"	1= strongly disagree, 2= disagree, 3= neither agree nor disagree, 4= agree, 5= strongly agree, don't know= blank
Wishful	To what extent do you agree with the following statement: "I believe there will be great advances in managing flood risk in the near future."	1= strongly disagree, 2= disagree, 3= neither agree nor disagree, 4= agree, 5= strongly agree, don't know= blank
Self-efficacy	Respondent's estimate of their ability to implement the measure	1=not at all confident; 2; 3; 4; 5=very confident
Response-efficacy	Respondent's estimate of the effectiveness of the measure	1=not effective at all; 2; 3; 4; 5=very effective
Response cost	Respondent's estimate of the cost of implementing the measure	1= not costly at all 2; 3; 4; 5=very costly

Table A-1 List of explanatory variables including names, description and coding

[1] The variable was constructed by choosing the value of either flood experience pre-2012 or flood experience post-2012 depending on whichever value was higher.

[2] The variable was constructed as the average between flood experience pre-2012 and flood-experience post 2012. If the average was an uneven number, the figure was rounded up.

Explanatory variable	Description	Coding
Friends	Friends having implemented flood risk adaptation measures	1= none of them, 2=hardly any of them, 3=few of them, 4=some of them, 5=most of them, don't know.
Implementation with neighbours	Implementation of any measure together with a neighbour. Specification of the measure.	1=yes, 2=no; specification of measure is open ended.
Existing schemes	Existence of schemes (e.g. through the local council or flood action group) to help with flooding on the household level	1=yes, 2=no
Support needed	Respondent's belief whether public authorities should help financially with flooding	1=yes, 2=no
Flood action group	Respondent's awareness of the existence of a flood action group in the community	1=yes, 0=no, don't know
Involvement	Involvement of the respondent in the flood action group	1=yes, 2=no
Usefulness	Usefulness of flood action group and explanation of rating	1= not at all useful, 2, 3, 4, 5= very useful, n/a. Explanation of rating as open ended question
Information on implementation	Information on how to use and implement specific flood adaptation measures	1=yes, 0=no
Information on flood warnings	Provision of information on flood warnings	1=yes, 0=no
Information on available measures	Provision of information on available flood adaptation measures	1=yes, 0=no
Information on flood risk strategy	Provision of information on the flood risk strategy of the council	1=yes, 0=no
No information	No information provided by the group	1=yes, 0=no

Table A-1 continued

Response variable	Description	Coding
Insurance pre-2012*	Extent of use of insurance as a flood adaptation measure until 2012	1=no insurance at all, 2, 3, 4, 5= the most comprehensive insurance cover, n/a
Sandbags pre-2012*	Extent of use of sandbags as a flood adaptation measure until 2012	1= no sandbags at all, 2, 3, 4, 5= a lot of sandbags, n/a
Floodgates pre-2012*	Extent of use of flood gates as a flood adaptation measure until 2012	1= no flood gate at all, 2, 3, 4, 5= a very sizeable flood gate, n/a
Flood warnings pre-2012*	Extent of use of flood warnings as a flood adaptation measure until 2012	1= no use of flood warnings, 2, 3, 4, 5 = to a great extent use of flood warning, n/a
Insurance post-2012*	Extent of use of insurance as a flood adaptation measure since 2012	1=no insurance at all, 2, 3, 4, 5= the most comprehensive insurance cover, n/a
Sandbags post-2012*	Extent of use of sandbags as a flood adaptation measure since 2012	1= no sandbags at all, 2,3,4,5= a lot of sandbags, n/a
Floodgates post-2012*	Extent of use of flood gates as a flood adaptation measure since 2012	1= no flood gate at all, 2, 3, 4, 5= a very sizeable flood gate, n/a
Flood warnings post-2012*	Extent of use of flood warnings as a flood adaptation measure since 2012	1= no use of flood warnings, 2, 3, 4, 5 = to a great extent use of flood warning, n/a
Future insurance	Extent of using insurance to manage flood risk in the nearby future	1=no insurance at all, 2, 3, 4, 5= the most comprehensive insurance cover, n/a
Future sandbags	Extent of using sandbags to manage flood risk in the nearby future.	1= no sandbags at all, 2,3,4,5= a lot of sandbags, n/a
Future floodgates	Extent of using floodgates to manage flood risk in the nearby future	1= no flood gate at all, 2, 3, 4, 5= a very sizeable flood gate, n/a
Future flood warnings	Extent of using flood warnings to manage flood risk in the nearby future.	1= no use of flood warnings, 2, 3, 4, 5 = to a great extent use of flood warning, n/a

Table A-2 List of response variables including names, description and coding. Variables with an asterisk were included as explanatory variables in the appropriate analyses

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1. Self-employment	1,00 *	0,42 *	-0,06	0,20	0,14	0,01	-0,42	-0,01 *	0,11	-0,02	-0,06	-0,22	0,28	0,05	-0,01	-0,24	-0,10	0,04	0,22	-0,15	-0,19	-0,14	-0,16	-0,10	0,25	0,06
2. Risk	0,42 *	1,00 *	-0,08	0,65 *	0,45 *	-0,01	-0,25 *	0,20	0,76	-0,16 *	-0,30	-0,08 *	0,63	0,12	-0,05	-0,01	0,07	0,06	0,14	0,14	0,08	-0,04	-0,02	0,26 *	0,51 *	0,33 *
3. Flood experience pre-2012	-0,06	-0,08	1,00 *	-0,03	0,55 *	0,95 *	0,01 *	-0,12	0,04	-0,12	-0,10	-0,13	0,01	-0,13	-0,12	-0,26 *	-0,07	-0,16	-0,08	-0,25 *	-0,06	-0,27	-0,24	-0,05	-0,04	-0,07
4. Flood experience post-2012	0,20 *	0,65 *	-0,03	1,00 *	0,78 *	0,09	-0,38 *	0,10 *	0,61	-0,13 *	-0,24	0,00 *	0,53	-0,04	0,04	0,13	-0,11	0,10	0,20	0,22 *	-0,08	0,13	0,03	-0,01	0,38 *	0,00
5. Average flood experience	0,14 *	0,45 *	0,55 *	0,78 *	1,00 *	0,62 *	-0,21 *	0,03	0,47	-0,11 *	-0,21	-0,10 *	0,42	-0,13	0,03	0,00	-0,06	-0,01	0,18	0,08	-0,04	-0,01	-0,08	-0,01	0,30 *	-0,01
6. Overall flood experience	0,01	-0,01	0,95 *	0,09	0,62 *	1,00 *	-0,06 *	-0,17	0,10	-0,07	-0,11	-0,10	0,06	-0,12	-0,02	-0,24	-0,05	-0,14	0,03	-0,22	-0,09	-0,29	-0,33 *	-0,06	0,06	-0,11
7. Existing schemes	-0,42 *	-0,25 *	0,01 *	-0,38 *	-0,21 *	-0,06 *	1,00 *	0,00	-0,19	0,14 *	0,21	0,25 *	-0,20	0,16	0,40	0,33 *	0,57	0,10	0,12	0,35 *	0,53	0,24	0,19	0,30	0,00	0,22
8. Support needed	-0,01	0,20	-0,12	0,10 *	0,03	-0,17	0,00	1,00 *	0,16	-0,28	-0,11	-0,39	0,28	-0,17	-0,07 *	0,03 *	-0,21 *	-0,23	-0,25	-0,15 *	-0,10 *	-0,12	-0,15	0,00	-0,05	-0,24
9. Threat	0,11	0,76	0,04	0,61	0,47	0,10	-0,19	0,16	1,00 *	-0,12	-0,37	-0,13	0,60 *	0,13	-0,08	0,13	0,14	0,04	0,01	0,19	0,13	0,04	0,05	0,21	0,41	0,35
10. Fatalism	-0,02 *	-0,16 *	-0,12	-0,13 *	-0,11 *	-0,07	0,14 *	-0,28	-0,12	1,00 *	0,11	0,15 *	-0,05	-0,09	-0,01	-0,12	-0,01	-0,01	-0,07	-0,08	0,10	-0,22	-0,17	0,00	0,15 *	-0,02 *
11. Avoidance	-0,06	-0,30	-0,10	-0,24	-0,21	-0,11	0,21	-0,11	-0,37	0,11	1,00 *	0,20	-0,39	-0,09	0,03	-0,19	0,00	-0,26	-0,20	-0,18	0,02	-0,05	-0,15	-0,02	-0,05	-0,10
12. Wishful	-0,22 *	-0,08 *	-0,13	0,00 *	-0,10 *	-0,10	0,25 *	-0,39	-0,13	0,15 *	0,20	1,00 *	-0,24	-0,03	0,07	0,13	0,30	-0,01 *	-0,01	0,22	0,21	0,17	0,11	-0,02	0,07	-0,08
13. Fear	0,28	0,63	0,01	0,53	0,42	0,06	-0,20	0,28	0,60 *	-0,05	-0,39	-0,24	1,00 *	-0,09	-0,09	0,03	0,09 *	0,01	0,15	0,07 *	0,04	0,07	0,08	0,25	0,39	0,32
14. Response efficacy (insurance)	0,05	0,12	-0,13	-0,04	-0,13	-0,12	0,16	-0,17	0,13	-0,09	-0,09	-0,03	-0,09	1,00 *	0,11	0,21	0,34 *	0,57 *	0,02	0,16	0,24 *	0,34 *	0,29 *	0,04	0,05	0,23
15. Response efficacy (sandbags)	-0,01	-0,05	-0,12	0,04	0,03	-0,02	0,40	-0,07 *	-0,08	-0,01	0,03	0,07	-0,09	0,11	1,00 *	0,29 *	0,15	0,15	0,58 *	0,10	0,09	0,27 *	0,15	0,11	0,31 *	0,04
16. Response efficacy (flood gates)	-0,24	-0,01	-0,26 *	0,13	0,00	-0,24	0,33 *	0,03 *	0,13	-0,12	-0,19	0,13	0,03	0,21	0,29 *	1,00 *	0,46 *	0,20	0,22 *	0,69 *	0,48 *	0,37 *	0,28 *	0,14	0,03	0,23
17. Response efficacy (flood warnings)	-0,10	0,07	-0,07	-0,11	-0,06	-0,05	0,57	-0,21 *	0,14	-0,01	0,00	0,30	0,09 *	0,34 *	0,15	0,46 *	1,00 *	0,28 *	0,18	0,43 *	0,67 *	0,33 *	0,26 *	0,16	0,05	0,28 *
18. Self-efficacy (insurance)	0,04	0,06	-0,16	0,10	-0,01	-0,14	0,10	-0,23	0,04	-0,01	-0,26	-0,01 *	0,01	0,57 *	0,15	0,20	0,28 *	1,00 *	0,55 *	0,34 *	0,38 *	0,33 *	0,40 *	-0,04	0,12	-0,04
19. Self-efficacy (sandbags)	0,22	0,14	-0,08	0,20	0,18	0,03	0,12	-0,25	0,01	-0,07	-0,20	-0,01	0,15	0,02	0,58 *	0,22 *	0,18	0,55 *	1,00 *	0,37 *	0,23 *	0,27 *	0,24 *	-0,02	0,31 *	0,02
20. Self-efficacy (flood gates)	-0,15	0,14	-0,25 *	0,22 *	0,08	-0,22	0,35 *	-0,15 *	0,19	-0,08	-0,18	0,22	0,07 *	0,16	0,10	0,69 *	0,43 *	0,34 *	0,37 *	1,00 *	0,67 *	0,23	0,18	0,17	-0,01	0,31 *
21. Self-efficacy (flood warnings)	-0,19	0,08	-0,06	-0,08	-0,04	-0,09	0,53	-0,10 *	0,13	0,10	0,02	0,21	0,04	0,24 *	0,09	0,48 *	0,67 *	0,38 *	0,23 *	0,67 *	1,00 *	0,12	0,14	0,13	0,00	0,23
22. Pre-2012 uptake (insurance)	-0,14	-0,04	-0,27	0,13	-0,01	-0,29	0,24	-0,12	0,04	-0,22	-0,05	0,17	0,07	0,34 *	0,27 *	0,37 *	0,33 *	0,33 *	0,27 *	0,23	0,12	1,00 *	0,88 *	-0,03	-0,03	0,19
23. Post-2012 uptake (insurance)	-0,16	-0,02	-0,24	0,03	-0,08	-0,33 *	0,19	-0,15	0,05	-0,17	-0,15	0,11	0,08	0,29 *	0,15	0,28 *	0,26 *	0,40 *	0,24 *	0,18	0,14	0,88 *	1,00 *	0,09	0,03	0,19
24. Pre-2012 uptake (sandbags)	-0,10 *	0,26 *	-0,05	-0,01	-0,01	-0,06	0,30	0,00	0,21	0,00	-0,02	-0,02	0,25	0,04	0,11	0,14	0,16	-0,04	-0,02	0,17	0,13	-0,03	0,09	1,00 *	0,70 *	0,56 *
25. Post-2012 uptake (sandbags)	0,25 *	0,51 *	-0,04	0,38 *	0,30 *	0,06	0,00	-0,05	0,41	0,15 *	-0,05	0,07	0,39	0,05	0,31 *	0,03	0,05	0,12	0,31 *	-0,01	0,00	-0,03	0,03	0,70 *	1,00 *	0,28
26. Pre-2012 uptake (flood gates)	0,06 *	0,33 *	-0,07	0,00	-0,01	-0,11	0,22	-0,24	0,35	-0,02 *	-0,10	-0,08	0,32	0,23	0,04	0,23	0,28 *	-0,04	0,02	0,31 *	0,23	0,19	0,19	0,56 *	0,28	1,00 *
27. Post-2012 uptake (gates)	0,09 *	0,36 *	-0,16	0,13	0,07	-0,17	0,39	-0,10 *	0,29	0,04 *	0,07	0,21	0,24	0,06	0,04	0,36 *	0,43 *	-0,13	0,02	0,51 *	0,49 *	0,14	0,10	0,52 *	0,32 *	0,75 *
28. Pre-2012 uptake (flood warnings)	-0,16	0,07	-0,08	-0,06	-0,01	-0,12	0,36	-0,13 *	0,15	0,22	0,02	0,00	0,18	0,24	0,13	0,22	0,31 *	0,03	-0,10	0,31 *	0,42 *	0,07	0,14	0,57 *	0,28 *	0,60 *
29. Post-2012 uptake (flood warnings)	-0,03	0,21	-0,14	-0,06	-0,01	-0,12	0,38	0,11 *	0,11	0,05	-0,01	0,17	0,10	0,26 *	0,09	0,22 *	0,42 *	0,12	0,09	0,44 *	0,64 *	0,09	0,10	0,33 *	0,21	0,28 *
30. Intended uptake (insurance)	-0,25	0,13	-0,19	0,26	0,11	-0,21	0,20	-0,19	0,22	-0,06	-0,25	0,23 *	0,02	0,44 *	0,32 *	0,31 *	0,24	0,42 *	0,30 *	0,17	0,12	0,77 *	0,76 *	0,06	0,22	0,21
31. Intended uptake (sandbags)	0,21 *	0,46 *	-0,11	0,34 *	0,25 *	-0,02	-0,03	0,04	0,40	0,07 *	-0,16	-0,02	0,39	0,01	0,41 *	0,19	0,04	0,11	0,40 *	0,00	0,02	0,04	0,09	0,51 *	0,86 *	0,28
32. Intended uptake (flood gates)	0,16 *	0,54 *	-0,14	0,50 *	0,35 *	-0,13	0,16 *	-0,03	0,40	-0,10 *	-0,10	0,26	0,37 *	0,02	0,08	0,47 *	0,25 *	-0,07	0,14	0,56 *	0,33 *	0,22	0,14	0,36 *	0,38 *	0,58 *
33. Intended uptake (flood warnings)	-0,04 *	0,43 *	0,00	0,14	0,21	0,04	0,38	0,12 *	0,31	0,08 *	-0,23	0,12 *	0,26	0,28 *	0,08	0,30 *	0,51 *	0,17	0,15	0,47 *	0,64 *	0,02	-0,01	0,20	0,21	0,25
34. Response cost (insurance)	0,06 *	0,22 *	-0,08	0,11	0,05	-0,10	-0,07	0,12	0,11	0,11	0,00	-0,18	0,27	-0,30 *	-0,14	-0,06	-0,01	-0,26 *	-0,13	-0,11	-0,03	-0,21	-0,17	0,00	-0,11	0,08
35. Response cost (sandbags)	0,43	0,05	0,19	0,11	0,20	0,17	-0,16	-0,24	0,05	0,12	-0,11	-0,17	0,02	-0,12	0,01	-0,28 *	-0,06	-0,04	-0,02	-0,22 *	-0,16	-0,16	-0,14	-0,21	-0,07	0,02
36. Response cost (flood gates)	-0,02	0,20	-0,13	0,31 *	0,10	-0,04	-0,29	0,14 *	0,25	0,01 *	-0,14	-0,12	0,17	-0,10	-0,14	-0,18	-0,18	-0,07	-0,17	-0,21	-0,23 *	-0,06	-0,17	-0,03	0,11	-0,23
37. Response cost (flood warnings)	0,04	0,11	-0,26 *	-0,08	-0,20	-0,35 *	0,23 *	0,06	0,17	0,12	-0,08	-0,27	0,13 *	0,07	0,04	0,04	0,15	-0,06	-0,08	0,00	-0,09	0,09	0,07	0,18	0,00	0,29 *
38. Friends	-0,19	0,00	0,04	-0,13	-0,11	0,06	0,53	0,01 *	0,15	0,00	0,13	0,09	0,08	0,17	0,25 *	0,10	0,37 *	-0,02	-0,01	0,04	0,27 *	0,09	-0,03	0,30 *	0,22	0,14
39. Neighbours	-0,04	0,09	-0,03	-0,11	-0,08	-0,04	0,53	0,12 *	0,18	-0,06	0,19	0,10	0,07	0,06	0,21	0,00	0,27 *	-0,02	0,14	0,17	0,26 *	0,13	0,04	0,35 *	0,26 *	0,27
40. Implementation with neighbourss	0,04	0,15	-0,12	0,14	0,08	-0,13	0,20	0,38	0,11 *	-0,11	0,12	0,04	0,16	0,02	0,17	0,11	0,14	-0,03	0,02	0,12	0,19	0,11	-0,12	0,11	0,12	0,09
41. Gender	-0,28	0,03	0,10	0,01	0,02	0,14	0,21	-0,05	-0,02	0,00	-0,12	0,12	0,14	-0,15	-0,08	-0,04	0,15	-0,08	0,07	0,11	0,11	-0,15	-0,09	0,07	-0,06	-0,09
42. Age	-0,20	-0,16	-0,07	-0,03	-0,11	-0,14	0,00	-0,06	0,02	-0,08	0,17	-0,11	-0,14	0,02	0,01	-0,06	-0,07	-0,23 *	-0,31 *	-0,16	-0,28 *	0,17	0,09	-0,08	-0,21	0,12
43. Education	0,02	-0,08	0,11	-0,18	-0,06	0,13	-0,02	-0,05	-0,10	0,04	-0,28	-0,01 *	-0,09	0,08	-0,06	0,07	0,13	0,07	0,02	0,05	0,16	0,01	0,02	-0,01	-0,08	-0,01
44. Income	-0,05	-0,23	0,32 *	-0,24	0,04	0,30 *	0,21	0,01	-0,10	-0,17	-0,02	0,17	-0,15	0,12	0,08	0,19	0,19	0,06	0,13	0,11	0,25 *	0,25	0,17	-0,07	-0,09	-0,04
45. Ownership	0,01	-0,16	0,23	0,06	0,18	0,29	-0,08	-0,55	-0,01	0,10	-0,17	0,12	0,12	-0,07	0,21	0,03	0,03	0,30	0,51 *	0,10	0,07	0,37	0,40	0,07	0,20	0,12
46. Flood action group	-0,08	-0,04	-0,08	-0,32 *	-0,31 *	-0,06	0,49	0,04 *	0,07	-0,07	0,13	0,04	-0,08	0,24	0,21	0,23	0,22	-0,06	0,02	0,14	0,11	0,33 *	0,17	0,12	-0,08	0,34
47. Involvement	0,25	0,19	-0,10	-0,17	-0,18	-0,07	0,20	0,05	0,14	0,05	-0,09	0,03	0,11	0,13	0,10	0,10	0,11	0,06	0,12	0,17	0,23	0,23	0,19	0,15	0,07	0,42 *
48. Information on flood warnings	-0,05	-0,01	0,04	-0,13	-0,03	0,04	0,34	-0,01 *	0,06	0,20	-0,04	0,21	-0,06	0,10	0,15	0,29 *	0,18	0,07	0,16	0,45 *	0,50 *	0,17	0,15	0,09	0,03	0,07
49. Information on available measures	-0,04 *	0,26 *	-0,25	0,07	-0,07	-0,27	0,23	0,09	0,14	0,18	-0,17	0,12	0,17	0,00	0,02	0,15	0,11	0,09	0,14	0,35 *	0,30 *	0,35 *	0,29 *	0,02	-0,07	0,24
50. Information on implementation	-0,05	0,09	-0,41 *	-0,06	-0,23	-0,43 *	0,44	0,33 *	0,07	0,13	-0,12	0,07	0,09	0,12	0,18	0,40 *	0,21	0,03	0,01	0,43 *	0,35 *	0,38 *	0,25	0,14	-0,08	0,30
51. Information on flood risk strategy	-0,02	0,10	-0,29 *	-0,18	-0,26 *	-0,26	0,41	0,17 *	0,08	0,19	-0,01	0,00	0,05	0,18	0,16	0,23	0,31 *	0,09	0,09	0,28 *	0,25 *	0,07	-0,10	0,10	-0,04	0,38 *
52. No information	0,01	0,16	-0,14	-0,02	-0,08	-0,09	0,15	0,03	0,12	0,36	0,10 *	0,07	0,10	-0,08	-0,02	0,12	-0,04	-0,07	0,07	0,29	0,21	-0,02	-0,14	-0,09	-0,11	0,14
53. Usefulness	0,22 *	0,28 *	-0,18	-0,09	-0,14	-0,13	0,18	0,00	0,26	0,04 *	-0,13	-0,01	0,23	0,24 *	0,10	0,19	0,34 *	0,10	0,13	0,26 *	0,36 *	0,33 *	0,29 *	0,12	0,04	0,43 *

Correlation values with (*) are significant at p=0.05

Table A3 Polychloric intercorrelation matrix of all response and explanatory variables, * indicates p<0.05

	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53
1. Self-employment	0,09	-0,16	-0,03	-0,25	0,21	0,16	-0,04	0,06	0,43 *	-0,02	0,04	-0,19	-0,04	0,04	-0,28	-0,20	0,02	-0,05	0,01	-0,08	0,25	-0,05	-0,04	-0,05	-0,02	0,01	0,22
2. Risk	0,36 *	0,07	0,21	0,13	0,46 *	0,54 *	0,43 *	0,22 *	0,05	0,20	0,11	0,00	0,09	0,15	0,03	-0,16	-0,08	-0,23	-0,16	-0,04	0,19	-0,01	0,26 *	0,09	0,10	0,16	0,28 *
3. Flood experience pre-2012	-0,16	-0,08	-0,14	-0,19	-0,11	-0,14	0,00	-0,08	0,19	-0,13	-0,26 *	0,04	-0,03	-0,12	0,10	-0,07	0,11	0,32 *	0,23	-0,08	-0,10	0,04	-0,25	-0,41 *	-0,29 *	-0,14	-0,18
4. Flood experience post-2012	0,13	-0,06	-0,06	0,26	0,34 *	0,50 *	0,14	0,11	0,11	0,31 *	-0,08	-0,13	-0,11	0,14	0,01	-0,03	-0,18	-0,24	0,06	-0,32 *	-0,17	-0,13	0,07	-0,06	-0,18	-0,02	-0,09
5. Average flood experience	0,07	-0,01	-0,01	0,11	0,25 *	0,35 *	0,21	0,05	0,20	0,10	-0,20	-0,11	-0,08	0,08	0,02	-0,11	-0,06	0,04	0,18	-0,31 *	-0,18	-0,03	-0,07	-0,23	-0,26 *	-0,08	-0,14
6. Overall flood experience	-0,17	-0,12	-0,12	-0,21	-0,02	-0,13	0,04	-0,10	0,17	-0,04	-0,35 *	0,06	-0,04	-0,13	0,14	-0,14	0,13	0,30 *	0,29	-0,06	-0,07	0,04	-0,27	-0,43 *	-0,26	-0,09	-0,13
7. Existing schemes	0,39	0,36	0,38	0,20	-0,03	0,16 *	0,38	-0,07	-0,16	-0,29	0,23 *	0,53	0,53	0,20	0,21	0,00	-0,02	0,21	-0,08	0,49	0,20	0,34	0,23	0,44	0,41	0,15	0,18
8. Support needed	-0,10 *	-0,13 *	0,11 *	-0,19	0,04	-0,03	0,12 *	0,12	-0,24	0,14 *	0,06	0,01 *	0,12 *	0,38	-0,05	-0,06	-0,05	0,01	-0,55	0,04 *	0,05	-0,01 *	0,09	0,33 *	0,17 *	0,03	0,00
9. Threat	0,29	0,15	0,11	0,22	0,40	0,40	0,31	0,11	0,05	0,25	0,17	0,15	0,18	0,11 *	-0,02	0,02	-0,10	-0,10	-0,01	0,07	0,14	0,06	0,14	0,07	0,08	0,12	0,26
10. Fatalism	0,04 *	0,22	0,05	-0,06	0,07 *	-0,10 *	0,08 *	0,11	0,12	0,01 *	0,12	0,00	-0,06	-0,11	0,00	-0,08	0,04	-0,17	0,10	-0,07	0,05	0,20	0,18	0,13	0,19	0,36	0,04 *
11. Avoidance	0,07	0,02	-0,01	-0,25	-0,16	-0,10	-0,23	0,00	-0,11	-0,14	-0,08	0,13	0,19	0,12	-0,12	0,17	-0,28	-0,02	-0,17	0,13	-0,09	-0,04	-0,17	-0,12	-0,01	0,10 *	-0,13
12. Wishful	0,21	0,00	0,17	0,23 *	-0,02	0,26	0,12 *	-0,18	-0,17	-0,12	-0,27	0,09	0,10	0,04	0,12	-0,11	-0,01 *	0,17	0,12	0,04	0,03	0,21	0,12	0,07	0,00	0,07	-0,01
13. Fear	0,24	0,18	0,10	0,02	0,39	0,37 *	0,26	0,27	0,02	0,17	0,13 *	0,08	0,07	0,16	0,14	-0,14	-0,09	-0,15	0,12	-0,08	0,11	-0,06	0,17	0,09	0,05	0,10	0,23
14. Response efficacy (insurance)	0,06	0,24	0,26 *	0,44 *	0,01	0,02	0,28 *	-0,30 *	-0,12	-0,10	0,07	0,17	0,06	0,02	-0,15	0,02	0,08	0,12	-0,07	0,24	0,13	0,10	0,00	0,12	0,18	-0,08	0,24 *
15. Response efficacy (sandbags)	0,04	0,13	0,09	0,32 *	0,41 *	0,08	0,08	-0,14	0,01	-0,14	0,04	0,25 *	0,21	0,17	-0,08	0,01	-0,06	0,08	0,21	0,21	0,10	0,15	0,02	0,18	0,16	-0,02	0,10
16. Response efficacy (flood gates)	0,36 *	0,22	0,22 *	0,31 *	0,19	0,47 *	0,30 *	-0,06	-0,28 *	-0,18	0,04	0,10	0,00	0,11	-0,04	-0,06	0,07	0,19	0,03	0,23	0,10	0,29 *	0,15	0,40 *	0,23	0,12	0,19
17. Response efficacy (flood warnings)	0,43 *	0,31 *	0,42 *	0,24	0,04	0,25 *	0,51 *	-0,01	-0,06	-0,18	0,15	0,37 *	0,27 *	0,14	0,15	-0,07	0,13	0,19	0,03	0,22	0,11	0,18	0,11	0,21	0,31 *	-0,04	0,34 *
18. Self-efficacy (insurance)	-0,13	0,03	0,12	0,42 *	0,11	-0,07	0,17	-0,26 *	-0,04	-0,07	-0,06	-0,02	-0,02	-0,03	-0,08	-0,23 *	0,07	0,06	0,30	-0,06	0,06	0,07	0,09	0,03	0,09	-0,07	0,10
19. Self-efficacy (sandbags)	0,02	-0,10	0,09	0,30 *	0,40 *	0,14	0,15	-0,13	-0,02	-0,17	-0,08	-0,01	0,14	0,02	0,07	-0,31 *	0,02	0,13	0,51 *	0,02	0,12	0,16	0,14	0,01	0,09	0,07	0,13
20. Self-efficacy (flood gates)	0,51 *	0,31 *	0,44 *	0,17	0,00	0,56 *	0,47 *	-0,11	-0,22 *	-0,21	0,00	0,04	0,17	0,12	0,11	-0,16	0,05	0,11	0,10	0,14	0,17	0,45 *	0,35 *	0,43 *	0,28 *	0,29	0,26 *
21. Self-efficacy (flood warnings)	0,49 *	0,42 *	0,64 *	0,12	0,02	0,33 *	0,64 *	-0,03	-0,16	-0,23 *	-0,09	0,27 *	0,26 *	0,19	0,11	-0,28 *	0,16	0,25 *	0,07	0,11	0,23	0,50 *	0,30 *	0,35 *	0,25 *	0,21	0,36 *
22. Pre-2012 uptake (insurance)	0,14	0,07	0,09	0,77 *	0,04	0,22	0,02	-0,21	-0,16	-0,06	0,09	0,09	0,13	0,11	-0,15	0,17	0,01	0,25	0,37	0,33 *	0,23	0,17	0,35 *	0,38 *	0,07	-0,02	0,33 *
23. Post-2012 uptake (insurance)	0,10	0,14	0,10	0,76 *	0,09	0,14	-0,01	-0,17	-0,14	-0,17	0,07	-0,03	0,04	-0,12	-0,09	0,09	0,02	0,17	0,40	0,17	0,19	0,15	0,29 *	0,25	-0,10	-0,14	0,29 *
24. Pre-2012 uptake (sandbags)	0,52 *	0,57 *	0,33 *	0,06	0,51 *	0,36 *	0,20	0,00	-0,21	-0,03	0,18	0,30 *	0,35 *	0,11	0,07	-0,08	-0,01	-0,07	0,07	0,12	0,15	0,09	0,02	0,14	0,10	-0,09	0,12
25. Post-2012 uptake (sandbags)	0,32 *	0,28 *	0,21	0,22	0,86 *	0,38 *	0,21	-0,11	-0,07	0,11	0,00	0,22	0,26 *	0,12	-0,06	-0,21	-0,08	-0,09	0,20	-0,08	0,07	0,03	-0,07	-0,08	-0,04	-0,11	0,04
26. Pre-2012 uptake (flood gates)	0,75 *	0,60 *	0,28 *	0,21	0,28	0,58 *	0,25	0,08	0,02	-0,23	0,29 *	0,14	0,27	0,09	-0,09	0,12	-0,01	-0,04	0,12	0,34	0,42 *	0,07	0,24	0,30	0,38 *	0,14	0,43 *
27. Post-2012 uptake (gates)	1,00 *	0,49 *	0,51 *	0,15	0,30 *	0,84 *	0,42 *	0,06	-0,04	-0,23	0,07	0,24	0,47 *	0,34 *	0,07	-0,06	0,09	0,05	0,01	0,27	0,50 *	0,27	0,36 *	0,49 *	0,31 *	0,15	0,52 *
28. Pre-2012 uptake (flood warnings)	0,49 *	1,00 *	0,66 *	0,17	0,21	0,31 *	0,44 *	0,08	-0,03	-0,07	0,18	0,22	0,25	0,12	-0,03	-0,05	0,03	-0,05	0,04	0,10	0,09	0,33 *	0,07	0,24	0,20	0,14	0,12
29. Post-2012 uptake (flood warnings)	0,51 *	0,66 *	1,00 *	0,16	0,23	0,37 *	0,74 *	-0,02	-0,22	-0,04	-0,16	0,22	0,42 *	0,31 *	0,13	-0,43 *	0,24 *	0,27 *	-0,04	0,21	0,34 *	0,57 *	0,22	0,37 *	0,21	0,23	0,39 *
30. Intended uptake (insurance)	0,15	0,17	0,16	1,00 *	0,32 *	0,28 *	0,20	-0,17	-0,14	0,02	0,01	0,11	0,12	-0,03	-0,04	0,11	0,00	0,12	0,31	0,12	0,07	0,14	0,28 *	0,23	0,03	-0,12	0,12
31. Intended uptake (sandbags)	0,30 *	0,21	0,23	0,32 *	1,00 *	0,42 *	0,26 *	-0,02	-0,08	0,13	-0,06	0,22	0,22	0,13	0,00	-0,14	-0,04	-0,03	0,22	-0,01	0,15	0,02	-0,04	-0,04	-0,02	-0,08	0,12
32. Intended uptake (flood gates)	0,84 *	0,31 *	0,37 *	0,28 *	0,42 *	1,00 *	0,46 *	0,00	-0,05	-0,10	0,00	0,07	0,23	0,28 *	0,05	-0,11	0,02	-0,03	-0,02	0,10	0,30 *	0,16	0,33 *	0,36 *	0,12	0,13	0,28 *
33. Intended uptake (flood warnings)	0,42 *	0,44 *	0,74 *	0,20	0,26 *	0,46 *	1,00 *	0,04	-0,24 *	0,00	-0,08	0,23	0,21	0,04	0,16	-0,32 *	0,20	0,12	-0,21	0,07	0,14	0,41 *	0,37 *	0,31 *	0,35 *	0,28	0,24
34. Response cost (insurance)	0,06	0,08	-0,02	-0,17	-0,02	0,00	0,04	1,00 *	0,34 *	0,20	0,30 *	0,04	-0,01	-0,07	0,33 *	-0,01	-0,08	-0,19	-0,13	-0,04	-0,06	-0,03	0,11	0,02	0,09	0,24	0,03
35. Response cost (sandbags)	-0,04	-0,03	-0,22	-0,14	-0,08	-0,05	-0,24 *	0,34 *	1,00 *	0,23 *	0,36 *	-0,15	-0,17	0,05	-0,04	0,03	0,03	-0,20	0,03	-0,12	-0,02	-0,23	-0,19	-0,18	-0,17	-0,14	-0,04
36. Response cost (flood gates)	-0,23	-0,07	-0,04	0,02	0,13	-0,10	0,00	0,20	0,23 *	1,00 *	0,08	0,10	-0,02	0,12	0,18	0,19	-0,01	-0,47 *	-0,13	0,07	-0,07	-0,21	0,04	-0,07	-0,09	0,14	-0,09
37. Response cost (flood warnings)	0,07	0,18	-0,16	0,01	-0,06	0,00	-0,08	0,30 *	0,36 *	0,08	1,00 *	0,18	0,05	0,17	0,02	0,21	-0,09	-0,20	-0,32	0,15	-0,18	-0,25	-0,07	0,09	0,12	-0,03	-0,08
38. Friends	0,24	0,22	0,22	0,11	0,22	0,07	0,23	0,04	-0,15	0,10	0,18	1,00 *	0,77 *	0,18	0,09	0,08	-0,08	0,20	0,11	0,36 *	0,05	0,26 *	0,05	0,13	0,06	0,01	0,12
39. Neighbours	0,47 *	0,25	0,42 *	0,12	0,22	0,23	0,21	-0,01	-0,17	-0,02	0,05	0,77 *	1,00 *	0,37 *	0,02	-0,04	-0,09	0,23	0,16	0,51 *	0,40 *	0,44 *	0,27 *	0,39 *	0,25 *	0,19	0,36 *
40. Implementation with neighbourss	0,34 *	0,12	0,31 *	-0,03	0,13	0,28 *	0,04	-0,07	0,05	0,12	0,17	0,18	0,37 *	1,00 *	-0,01	-0,10	0,08	0,14	-0,13	0,21	0,25	0,08	0,06	0,37 *	0,15	0,04	0,24
41. Gender	0,07	-0,03	0,13	-0,04	0,00	0,05	0,16	0,33 *	-0,04	0,18	0,02	0,09	0,02	-0,01	1,00 *	-0,10	0,18	-0,09	-0,05	0,03	-0,06	-0,16	-0,12	-0,20	-0,17	-0,07	-0,01
42. Age	-0,06	-0,05	-0,43 *	0,11	-0,14	-0,11	-0,32 *	-0,01	0,03	0,19	0,21	0,08	-0,04	-0,10	-0,10	1,00 *	-0,32 *	-0,41 *	-0,13	0,09	-0,15	-0,27 *	0,06	0,04	0,10	-0,06	-0,11
43. Education	0,09	0,03	0,24 *	0,00	-0,04	0,02	0,20	-0,08	0,03	-0,01	-0,09	-0,08	-0,09	0,08	0,18	-0,32 *	1,00 *	0,37 *	0,15	-0,09	0,25 *	0,08	0,08	0,08	-0,07	-0,24	0,29 *
44. Income	0,05	-0,05	0,27 *	0,12	-0,03	-0,03	0,12	-0,19	-0,20	-0,47 *	-0,20	0,20	0,23	0,14	-0,09	-0,41 *	0,37 *	1,00 *	0,33	0,18	0,20	0,46 *	-0,09	0,08	-0,06	-0,11	0,21
45. Ownership	0,01	0,04	-0,04	0,31	0,22	-0,02	-0,21	-0,13	0,03	-0,13	-0,32	0,11	0,16	-0,13	-0,05	-0,13	0,15	0,33	1,00 *	0,03	0,24	0,32	0,13	-0,07	-0,22	-0,01	0,27
46. Flood action group	0,27	0,10	0,21	0,12	-0,01	0,10	0,07	-0,04	-0,12	0,07	0,15	0,36 *	0,51 *	0,21	0,03	0,09	-0,09	0,18	0,03	1,00 *	0,68 *	0,36 *	0,32 *	0,50 *	0,48 *	0,53 *	0,59 *
47. Involvement	0,50 *	0,09	0,34 *	0,07	0,15	0,30 *	0,14	-0,06	-0,02	-0,07	-0,18	0,05	0,40 *	0,25	-0,06	-0,15	0,25 *	0,20	0,24	0,68 *	1,00 *	0,43 *	0,54 *	0,63 *	0,46 *	0,43 *	0,90 *
48. Information on flood warnings	0,27	0,33 *	0,57 *	0,14	0,02	0,16	0,41 *	-0,03	-0,23	-0,21	-0,25	0,26 *	0,44 *	0,08	-0,16	-0,27 *	0,08	0,46 *	0,32	0,36 *	0,43 *	1,00 *	0,53 *	0,57 *	0,27	0,58 *	0,42 *
49. Information on available measures	0,36 *	0,07	0,22	0,28 *	-0,04	0,33 *	0,37 *	0,11	-0,19	0,04	-0,07	0,05	0,27 *	0,06	-0,12	0,06	0,08	-0,09	0,13	0,32 *	0,54 *	0,53 *	1,00 *	0,79 *	0,57 *	0,63	0,53 *
50. Information on implementation	0,49 *	0,24	0,37 *	0,23	-0,04	0,36 *	0,31 *	0,02	-0,18	-0,07	0,09	0,13	0,39 *	0,37 *	-0,20	0,04	0,08	0,08	-0,07	0,50 *	0,63 *	0,57 *	0,79 *	1,00 *	0,69 *	0,52 *	0,59 *
51. Information on flood risk strategy	0,31 *	0,20	0,21	0,03	-0,02	0,12	0,35 *	0,09	-0,17	-0,09	0,12	0,06	0,25 *	0,15	-0,17	0,10	-0,07	-0,06	-0,22	0,48 *	0,46 *	0,27	0,57 *	0,69 *	1,00 *	0,58 *	0,41 *
52. No information	0,15	0,14	0,23	-0,12	-0,08	0,13	0,28	0,24	-0,14	0,14	-0,03	0,01	0,19	0,04	-0,07	-0,06	-0,24	-0,11	-0,01	0,53 *	0,43 *	0,58 *	0,63	0,52 *	0,58 *	1,00 *	0,35 *
53. Usefulness	0,52 *	0,12	0,39 *	0,12	0,12	0,28 *	0,24	0,03	-0,04	-0,09	-0,08	0,12	0,36 *	0,24	-0,01	-0,11	0,29 *	0,21	0,27	0,59 *	0,90 *	0,42 *	0,53 *	0,59 *	0,41 *	0,35 *	1,00 *

Correlation values with (*) are significant at p=0.05

Table A3 continued

	Sample	Z	Y	X	1 Z=aY	2 Z=bX	3 Z = aY + bX vs. Z = aY	4 Y= bX
1	All communities	Post-2012 uptake (insurance)	Self-efficacy (insurance)	Flood action group	0.002 *	0.183	0.132	0.935
2	All communities	Post-2012 uptake (insurance)	Response-efficacy (insurance)	Flood action group	0.018 *	0.425	0.542	0.317
3	All communities	Intended uptake (insurance)	Self-efficacy (insurance)	Flood action group	0.002 *	0.470	0.434	0.953
4	All communities	Intended uptake (insurance)	Response-efficacy (insurance)	Flood action group	0.002 *	0.366	0.501	0.280
5	Communities with a group	Post-2012 uptake (insurance)	Self-efficacy (insurance)	Usefulness	0.006 *	0.128	0.384	0.120
6	Communities with a group	Post-2012 uptake (insurance)	Response-efficacy (insurance)	Usefulness	0.133	0.093	0.183	0.017 *
7	Communities with a group	Intended uptake (insurance)	Self-efficacy (insurance)	Usefulness	0.028 *	0.780	0.881	0.246
8	Communities with a group	Intended uptake (insurance)	Response-efficacy (insurance)	Usefulness	0.013 *	0.700	0.867	0.059
9	Communities with a group	Post-2012 uptake (insurance)	Self-efficacy (insurance)	Information on the implementation of measures	0.006 *	0.232	0.325	0.444
10	Communities with a group	Post-2012 uptake (insurance)	Response-efficacy (insurance)	Information on the implementation of measures	0.052	0.211	0.208	0.562
11	Communities with a group	Intended uptake (insurance)	Self-efficacy (insurance)	Information on the implementation of measures	0.030 *	0.106	0.152	0.561
12	Communities with a group	Intended uptake (insurance)	Response-efficacy (insurance)	Information on the implementation of measures	0.011 *	0.045 *	0.055	0.602

Table A-4 Complete mediation analysis for all response variables to test for a complete mediating effect of threat and coping appraisal on flood experience and partial and complete mediation effects of threat and coping appraisal on the flood action group variables.

	Sample	Z	Y	X	1 Z=aY	2 Z=bX	3 Z = aY + bX vs. Z = aY	4 Y= bX
13	Communities with a group	Post-2012 uptake (insurance)	Self-efficacy (insurance)	Information on available measures	0.006 *	0.056	0.068	0.497
14	Communities with a group	Post-2012 uptake (insurance)	Response-efficacy (insurance)	Information on available measures	0.052	0.043 *	0.029 *	0.742
15	Communities with a group	Intended uptake (insurance)	Self-efficacy (insurance)	Information on available measures	0.030 *	0.047 *	0.061	0.559
16	Communities with a group	Intended uptake (insurance)	Response-efficacy (insurance)	Information on available measures	0.011 *	0.017 *	0.008 *	0.780
17	Communities with a group	Post-2012 uptake (insurance)	Self-efficacy (insurance)	Involvement	0.006 *	0.282	0.596	0.245
18	Communities with a group	Post-2012 uptake (insurance)	Response-efficacy (insurance)	Involvement	0.052	0.215	0.306	0.417
19	Communities with a group	Intended uptake (insurance)	Self-efficacy (insurance)	Involvement	0.030 *	0.756	0.989	0.407
20	Communities with a group	Intended uptake (insurance)	Response-efficacy (insurance)	Involvement	0.011 *	1.000	0.882	0.754
21	All communities	Post-2012 uptake (insurance)	Self-efficacy (insurance)	Existing schemes	0.005 *	0.132	0.301	0.096
22	All communities	Post-2012 uptake (insurance)	Response-efficacy (insurance)	Existing schemes	0.035 *	0.163	0.175	0.714
23	All communities	Intended uptake (insurance)	Self-efficacy (insurance)	Existing schemes	0.009 *	0.428	0.670	0.127
24	All communities	Intended uptake (insurance)	Response-efficacy (insurance)	Existing schemes	0.007 *	0.371	0.428	0.664
25	All communities	Post-2012 uptake (insurance)	Self-efficacy (insurance)	Pre-2012 flood experience	0.003 *	0.062	0.143	0.231

Table A-4 continued

					1	2	3	4
	Sample	**Z**	**Y**	**X**	**Z=aY**	**Z=bX**	**Z = aY + bX vs. Z = aY**	**Y= bX**
26	All communities	Post-2012 uptake (insurance)	Response-efficacy (insurance)	Pre-2012 flood experience	0.018 *	0.121	0.132	0.700
27	All communities	Intended uptake (insurance)	Self-efficacy (insurance)	Pre-2012 flood experience	0.004 *	0.378	0.572	0.316
28	All communities	Intended uptake (insurance)	Response-efficacy (insurance)	Pre-2012 flood experience	0.002 *	0.304	0.280	0.716
29	All communities	Post-2012 uptake (insurance)	Self-efficacy (insurance)	Post-2012 flood experience	0.014 *	0.982	0.933	0.918
30	All communities	Post-2012 uptake (insurance)	Response-efficacy (insurance)	Post-2012 flood experience	0.035 *	0.956	0.979	0.797
31	All communities	Intended uptake (insurance)	Self-efficacy (insurance)	Post-2012 flood experience	0.011 *	0.433	0.427	0.922
32	All communities	Intended uptake (insurance)	Response-efficacy (insurance)	Post-2012 flood experience	0.014 *	0.457	0.332	0.658
33	All communities	Post-2012 uptake (insurance)	Self-efficacy (insurance)	Average flood experience	0.003 *	0.611	0.800	0.530
34	All communities	Post-2012 uptake (insurance)	Response-efficacy (insurance)	Average flood experience	0.018 *	0.642	0.716	0.714
35	All communities	Intended uptake (insurance)	Self-efficacy (insurance)	Average flood experience	0.004 *	0.411	0.285	0.584
36	All communities	Intended uptake (insurance)	Response-efficacy (insurance)	Average flood experience	0.002 *	0.506	0.382	0.549
37	All communities	Post-2012 uptake (insurance)	Self-efficacy (insurance)	Overall flood experience	0.003 *	0.036 *	0.080	0.272
38	All communities	Post-2012 uptake (insurance)	Response-efficacy (insurance)	Overall flood experience	0.018 *	0.026 *	0.028 *	0.515

Table A-4 continued

	Sample	Z	Y	X	1 Z=aY		2 Z=bX		3 Z = aY + bX vs. Z = aY		4 Y= bX	
39	All communities	Intended uptake (insurance)	Self-efficacy (insurance)	Overall flood experience	0.004	*	0.170		0.265		0.362	
40	All communities	Intended uptake (insurance)	Response-efficacy (insurance)	Overall flood experience	0.002	*	0.175		0.176		0.524	
41	All communities	Post-2012 uptake (insurance)	Risk	Pre-2012 flood experience	0.848		0.123		0.122		0.801	
42	All communities	Intended uptake (insurance)	Risk	Pre-2012 flood experience	0.208		0.176		0.183		0.904	
43	All communities	Post-2012 uptake (insurance)	Risk	Post-2012 flood experience	0.678		0.887		0.711		0.000	*
44	All communities	Intended uptake (insurance)	Risk	Post-2012 flood experience	0.096		0.105		0.373		0.000	*
45	All communities	Post-2012 uptake (insurance)	Risk	Average flood experience	0.748		0.630		0.519		0.000	*
46	All communities	Intended uptake (insurance)	Risk	Average flood experience	0.171		0.219		0.451		0.000	*
47	All communities	Post-2012 uptake (insurance)	Risk	Overall flood experience	0.848		0.027	*	0.026	*	0.325	
48	All communities	Intended uptake (insurance)	Risk	Overall flood experience	0.208		0.096		0.085		0.336	
49	All communities	Post-2012 uptake (insurance)	Threat	Pre-2012 flood experience	0.438		0.123		0.113		0.433	
50	All communities	Intended uptake (insurance)	Threat	Pre-2012 flood experience	0.760		0.176		0.176		0.527	
51	All communities	Post-2012 uptake (insurance)	Threat	Post-2012 flood experience	0.393		0.887		0.633		0.000	*

Table A-4 continued

	Sample	Z	Y	X	1 Z=aY		2 Z=bX		3 Z = aY + bX vs. Z = aY		4 Y= bX	
52	All communities	Intended uptake (insurance)	Threat	Post-2012 flood experience	0.621		0.105		0.120		0.000	*
53	All communities	Post-2012 uptake (insurance)	Threat	Average flood experience	0.377		0.630		0.434		0.001	*
54	All communities	Intended uptake (insurance)	Threat	Average flood experience	0.697		0.219		0.243		0.001	*
55	All communities	Post-2012 uptake (insurance)	Threat	Overall flood experience	0.438		0.027	*	0.022	*	0.251	
56	All communities	Intended uptake (insurance)	Threat	Overall flood experience	0.760		0.096		0.093		0.264	
57	All communities	Post-2012 uptake (gates)	Self-efficacy (flood gates)	Flood action group	0.000	*	0.193		0.366		0.205	
58	All communities	Post-2012 uptake (gates)	Response-efficacy (gates)	Flood action group	0.001	*	0.116		0.255		0.247	
59	All communities	Intended uptake (gates)	Self-efficacy (flood gates)	Flood action group	0.000	*	0.643		0.537		0.960	
60	All communities	Intended uptake (gates)	Response-efficacy (gates)	Flood action group	0.000	*	0.706		0.971		0.724	
61	Communities with a group	Post-2012 uptake (gates)	Self-efficacy (flood gates)	Usefulness	0.002	*	0.002	*	0.007	*	0.038	*
62	Communities with a group	Post-2012 uptake (gates)	Response-efficacy (gates)	Usefulness	0.003	*	0.001	*	0.004	*	0.025	*
63	Communities with a group	Intended uptake (gates)	Self-efficacy (flood gates)	Usefulness	0.000	*	0.007	*	0.036	*	0.092	
64	Communities with a group	Intended uptake (gates)	Response-efficacy (gates)	Usefulness	0.000	*	0.004	*	0.022	*	0.114	

Table A-4 continued

	Sample	Z	Y	X	1 Z=aY	2 Z=bX	3 Z = aY + bX vs. Z = aY	4 Y= bX
65	Communities with a group	Post-2012 uptake (gates)	Self-efficacy (flood gates)	Information on the implementation of measures	0.001 *	0.001 *	0.014 *	0.001 *
66	Communities with a group	Post-2012 uptake (gates)	Response-efficacy (gates)	Information on the implementation of measures	0.002 *	0.000 *	0.005 *	0.002 *
67	Communities with a group	Intended uptake (gates)	Self-efficacy (flood gates)	Information on the implementation of measures	0.000 *	0.001 *	0.047 *	0.000 *
68	Communities with a group	Intended uptake (gates)	Response-efficacy (gates)	Information on the implementation of measures	0.000 *	0.000 *	0.018 *	0.002 *
69	Communities with a group	Post-2012 uptake (gates)	Self-efficacy (flood gates)	Information on available measures	0.001 *	0.005 *	0.037 *	0.006 *
70	Communities with a group	Post-2012 uptake (gates)	Response-efficacy (gates)	Information on available measures	0.002 *	0.002 *	0.008 *	0.071
71	Communities with a group	Intended uptake (gates)	Self-efficacy (flood gates)	Information on available measures	0.000 *	0.003 *	0.100	0.003 *
72	Communities with a group	Intended uptake (gates)	Response-efficacy (gates)	Information on available measures	0.000 *	0.002 *	0.052	0.030 *
73	Communities with a group	Post-2012 uptake (gates)	Self-efficacy (flood gates)	Involvement	0.001 *	0.002 *	0.001 *	0.779
74	Communities with a group	Post-2012 uptake (gates)	Response-efficacy (gates)	Involvement	0.002 *	0.001 *	0.002 *	0.542
75	Communities with a group	Intended uptake (gates)	Self-efficacy (flood gates)	Involvement	0.000 *	0.002 *	0.002 *	0.697
76	Communities with a group	Intended uptake (gates)	Response-efficacy (gates)	Involvement	0.000 *	0.003 *	0.003 *	0.888
77	All communities	Post-2012 uptake (gates)	Self-efficacy (flood gates)	Existing schemes	0.000 *	0.025 *	0.281	0.006 *

Table A-4 continued

	Sample	Z	Y	X	1 Z=aY	2 Z=bX	3 Z = aY + bX vs. Z = aY	4 Y= bX
78	All communities	Post-2012 uptake (gates)	Response-efficacy (gates)	Existing schemes	0.005 *	0.015 *	0.053	0.069
79	All communities	Intended uptake (gates)	Self-efficacy (flood gates)	Existing schemes	0.000 *	0.239	0.751	0.043 *
80	All communities	Intended uptake (gates)	Response-efficacy (gates)	Existing schemes	0.000 *	0.129	0.247	0.230
81	All communities	Post-2012 uptake (gates)	Self-efficacy (flood gates)	Pre-2012 flood experience	0.000 *	0.374	0.924	0.055
82	All communities	Post-2012 uptake (gates)	Response-efficacy (gates)	Pre-2012 flood experience	0.000 *	0.466	0.990	0.045 *
83	All communities	Intended uptake (gates)	Self-efficacy (flood gates)	Pre-2012 flood experience	0.000 *	0.370	0.895	0.070
84	All communities	Intended uptake (gates)	Response-efficacy (gates)	Pre-2012 flood experience	0.000 *	0.627	0.470	0.036 *
85	All communities	Post-2012 uptake (gates)	Self-efficacy (flood gates)	Post-2012 flood experience	0.000 *	0.170	0.737	0.007 *
86	All communities	Post-2012 uptake (gates)	Response-efficacy (gates)	Post-2012 flood experience	0.000 *	0.179	0.289	0.166
87	All communities	Intended uptake (gates)	Self-efficacy (flood gates)	Post-2012 flood experience	0.000 *	0.000 *	0.006 *	0.004 *
88	All communities	Intended uptake (gates)	Response-efficacy (gates)	Post-2012 flood experience	0.000 *	0.000 *	0.002 *	0.028 *
89	All communities	Post-2012 uptake (gates)	Self-efficacy (flood gates)	Average flood experience	0.000 *	0.305	0.828	0.067
90	All communities	Post-2012 uptake (gates)	Response-efficacy (gates)	Average flood experience	0.000 *	0.290	0.336	0.503

Table A-4 continued

	Sample	Z	Y	X	1 Z=aY		2 Z=bX		3 Z = aY + bX vs. Z = aY		4 Y= bX	
91	All communities	Intended uptake (gates)	Self-efficacy (flood gates)	Average flood experience	0.000	*	0.003	*	0.021	*	0.050	*
92	All communities	Intended uptake (gates)	Response-efficacy (gates)	Average flood experience	0.000	*	0.003	*	0.004	*	0.282	
93	All communities	Post-2012 uptake (gates)	Self-efficacy (flood gates)	Overall flood experience	0.000	*	0.392		0.910		0.087	
94	All communities	Post-2012 uptake (gates)	Response-efficacy (gates)	Overall flood experience	0.000	*	0.478		0.989		0.077	
95	All communities	Intended uptake (gates)	Self-efficacy (flood gates)	Overall flood experience	0.000	*	0.475		0.794		0.102	
96	All communities	Intended uptake (gates)	Response-efficacy (gates)	Overall flood experience	0.000	*	0.757		0.389		0.058	
97	All communities	Post-2012 uptake (gates)	Risk	Pre-2012 flood experience	0.003	*	0.297		0.323		0.650	
98	All communities	Intended uptake (gates)	Risk	Pre-2012 flood experience	0.000	*	0.357		0.271		0.837	
99	All communities	Post-2012 uptake (gates)	Risk	Post-2012 flood experience	0.003	*	0.330		0.620		0.000	*
100	All communities	Intended uptake (gates)	Risk	Post-2012 flood experience	0.000	*	0.000	*	0.019	*	0.000	*
101	All communities	Post-2012 uptake (gates)	Risk	Average flood experience	0.005	*	0.510		0.621		0.000	*
102	All communities	Intended uptake (gates)	Risk	Average flood experience	0.000	*	0.001	*	0.128		0.000	*
103	All communities	Post-2012 uptake (gates)	Risk	Overall flood experience	0.003	*	0.320		0.260		0.662	

Table A-4 continued

	Sample	Z	Y	X	1 Z=aY		2 Z=bX		3 Z = aY + bX vs. Z = aY		4 Y= bX	
104	All communities	Intended uptake (gates)	Risk	Overall flood experience	0.000	*	0.459		0.222		0.499	
105	All communities	Post-2012 uptake (gates)	Threat	Pre-2012 flood experience	0.041	*	0.297		0.260		0.660	
106	All communities	Intended uptake (gates)	Threat	Pre-2012 flood experience	0.002	*	0.357		0.324		0.774	
107	All communities	Post-2012 uptake (gates)	Threat	Post-2012 flood experience	0.073		0.330		0.655		0.000	*
108	All communities	Intended uptake (gates)	Threat	Post-2012 flood experience	0.003	*	0.000	*	0.000	*	0.000	*
109	All communities	Post-2012 uptake (gates)	Threat	Average flood experience	0.055		0.510		0.896		0.001	*
110	All communities	Intended uptake (gates)	Threat	Average flood experience	0.003	*	0.001	*	0.009	*	0.001	*
111	All communities	Post-2012 uptake (gates)	Threat	Overall flood experience	0.041	*	0.320		0.243		0.353	
112	All communities	Intended uptake (gates)	Threat	Overall flood experience	0.002	*	0.459		0.351		0.426	
113	All communities	Post-2012 uptake (sandbags)	Self-efficacy (sandbags)	Flood action group	0.001	*	0.562		0.839		0.687	
114	All communities	Post-2012 uptake (sandbags)	Response-efficacy (sandbags)	Flood action group	0.013	*	0.803		0.673		0.267	
115	All communities	Intended uptake (sandbags)	Self-efficacy (sandbags)	Flood action group	0.000	*	0.976		0.893		0.379	
116	All communities	Intended uptake (sandbags)	Response-efficacy (sandbags)	Flood action group	0.001	*	0.730		0.849		0.160	

Table A-4 continued

	Sample	Z	Y	X	1 Z=aY	2 Z=bX	3 Z = aY + bX vs. Z = aY	4 Y= bX
117	Communities with a group	Post-2012 uptake (sandbags)	Self-efficacy (sandbags)	Usefulness	0.013 *	0.264	0.386	0.089
118	Communities with a group	Post-2012 uptake (sandbags)	Response-efficacy (sandbags)	Usefulness	0.046 *	0.231	0.241	0.237
119	Communities with a group	Intended uptake (sandbags)	Self-efficacy (sandbags)	Usefulness	0.006 *	0.137	0.231	0.088
120	Communities with a group	Intended uptake (sandbags)	Response-efficacy (sandbags)	Usefulness	0.018 *	0.088	0.087	0.491
121	Communities with a group	Post-2012 uptake (sandbags)	Self-efficacy (sandbags)	Information on the implementation of measures	0.014 *	0.919	0.898	0.823
122	Communities with a group	Post-2012 uptake (sandbags)	Response-efficacy (sandbags)	Information on the implementation of measures	0.031 *	0.954	0.964	0.394
123	Communities with a group	Intended uptake (sandbags)	Self-efficacy (sandbags)	Information on the implementation of measures	0.003 *	0.925	0.999	0.812
124	Communities with a group	Intended uptake (sandbags)	Response-efficacy (sandbags)	Information on the implementation of measures	0.004 *	0.860	0.998	0.310
125	Communities with a group	Post-2012 uptake (sandbags)	Self-efficacy (sandbags)	Information on available measures	0.014 *	0.582	0.645	0.671
126	Communities with a group	Post-2012 uptake (sandbags)	Response-efficacy (sandbags)	Information on available measures	0.031 *	0.623	0.607	0.543
127	Communities with a group	Intended uptake (sandbags)	Self-efficacy (sandbags)	Information on available measures	0.003 *	0.547	0.630	0.395
128	Communities with a group	Intended uptake (sandbags)	Response-efficacy (sandbags)	Information on available measures	0.004 *	0.393	0.398	0.505
129	Communities with a group	Post-2012 uptake (sandbags)	Self-efficacy (sandbags)	Involvement	0.014 *	0.204	0.269	0.251

Table A-4 continued

	Sample	Z	Y	X	1 Z=aY	2 Z=bX	3 Z = aY + bX vs. Z = aY	4 Y= bX
130	Communities with a group	Post-2012 uptake (sandbags)	Response-efficacy (sandbags)	Involvement	0.031 *	0.134	0.171	0.096
131	Communities with a group	Intended uptake (sandbags)	Self-efficacy (sandbags)	Involvement	0.003 *	0.080	0.097	0.322
132	Communities with a group	Intended uptake (sandbags)	Response-efficacy (sandbags)	Involvement	0.004 *	0.048 *	0.050	0.359
133	All communities	Post-2012 uptake (sandbags)	Self-efficacy (sandbags)	Existing schemes	0.015 *	0.634	0.839	0.252
134	All communities	Post-2012 uptake (sandbags)	Response-efficacy (sandbags)	Existing schemes	0.059	0.730	0.885	0.008 *
135	All communities	Intended uptake (sandbags)	Self-efficacy (sandbags)	Existing schemes	0.005 *	0.877	0.735	0.115
136	All communities	Intended uptake (sandbags)	Response-efficacy (sandbags)	Existing schemes	0.003 *	0.905	0.407	0.007 *
137	All communities	Post-2012 uptake (sandbags)	Self-efficacy (sandbags)	Pre-2012 flood experience	0.004 *	0.975	0.991	0.857
138	All communities	Post-2012 uptake (sandbags)	Response-efficacy (sandbags)	Pre-2012 flood experience	0.005 *	0.886	0.694	0.542
139	All communities	Intended uptake (sandbags)	Self-efficacy (sandbags)	Pre-2012 flood experience	0.000 *	0.497	0.480	0.564
140	All communities	Intended uptake (sandbags)	Response-efficacy (sandbags)	Pre-2012 flood experience	0.000 *	0.538	0.666	0.454
141	All communities	Post-2012 uptake (sandbags)	Self-efficacy (sandbags)	Post-2012 flood experience	0.012 *	0.002 *	0.006 *	0.085
142	All communities	Post-2012 uptake (sandbags)	Response-efficacy (sandbags)	Post-2012 flood experience	0.019 *	0.001 *	0.001 *	0.719

Table A-4 continued

	Sample	Z	Y	X	1 Z=aY	2 Z=bX	3 Z = aY + bX vs. Z = aY	4 Y= bX
143	All communities	Intended uptake (sandbags)	Self-efficacy (sandbags)	Post-2012 flood experience	0.002 *	0.006 *	0.020 *	0.167
144	All communities	Intended uptake (sandbags)	Response-efficacy (sandbags)	Post-2012 flood experience	0.001 *	0.010 *	0.022 *	0.412
145	All communities	Post-2012 uptake (sandbags)	Self-efficacy (sandbags)	Average flood experience	0.003 *	0.018 *	0.065	0.054
146	All communities	Post-2012 uptake (sandbags)	Response-efficacy (sandbags)	Average flood experience	0.001 *	0.010 *	0.016 *	0.487
147	All communities	Intended uptake (sandbags)	Self-efficacy (sandbags)	Average flood experience	0.000 *	0.039 *	0.149	0.142
148	All communities	Intended uptake (sandbags)	Response-efficacy (sandbags)	Average flood experience	0.000 *	0.048 *	0.154	0.194
149	All communities	Post-2012 uptake (sandbags)	Self-efficacy (sandbags)	Overall flood experience	0.004 *	0.503	0.536	0.750
150	All communities	Post-2012 uptake (sandbags)	Response-efficacy (sandbags)	Overall flood experience	0.005 *	0.396	0.307	0.736
151	All communities	Intended uptake (sandbags)	Self-efficacy (sandbags)	Overall flood experience	0.000 *	0.783	0.988	0.786
152	All communities	Intended uptake (sandbags)	Response-efficacy (sandbags)	Overall flood experience	0.000 *	0.746	0.783	0.955
153	All communities	Post-2012 uptake (sandbags)	Risk	Pre-2012 flood experience	0.000 *	0.926	0.717	0.795
154	All communities	Intended uptake (sandbags)	Risk	Pre-2012 flood experience	0.000 *	0.422	0.345	0.905
155	All communities	Post-2012 uptake (sandbags)	Risk	Post-2012 flood experience	0.000 *	0.001 *	0.171	0.000 *

Table A-4 continued

	Sample	Z	Y	X	1 Z=aY		2 Z=bX		3 Z = aY + bX vs. Z = aY		4 Y= bX	
156	All communities	Intended uptake (sandbags)	Risk	Post-2012 flood experience	0.000	*	0.004	*	0.414		0.000	*
157	All communities	Post-2012 uptake (sandbags)	Risk	Average flood experience	0.000	*	0.016	*	0.363		0.000	*
158	All communities	Intended uptake (sandbags)	Risk	Average flood experience	0.000	*	0.031	*	0.573		0.000	*
159	All communities	Post-2012 uptake (sandbags)	Risk	Overall flood experience	0.000	*	0.545		0.827		0.393	
160	All communities	Intended uptake (sandbags)	Risk	Overall flood experience	0.000	*	0.893		0.814		0.471	
161	All communities	Post-2012 uptake (sandbags)	Threat	Pre-2012 flood experience	0.001	*	0.926		0.721		0.582	
162	All communities	Intended uptake (sandbags)	Threat	Pre-2012 flood experience	0.000	*	0.422		0.362		0.607	
163	All communities	Post-2012 uptake (sandbags)	Threat	Post-2012 flood experience	0.001	*	0.001	*	0.030	*	0.000	*
164	All communities	Intended uptake (sandbags)	Threat	Post-2012 flood experience	0.001	*	0.004	*	0.063		0.000	*
165	All communities	Post-2012 uptake (sandbags)	Threat	Average flood experience	0.001	*	0.016	*	0.164		0.000	*
166	All communities	Intended uptake (sandbags)	Threat	Average flood experience	0.001	*	0.031	*	0.231		0.001	*
167	All communities	Post-2012 uptake (sandbags)	Threat	Overall flood experience	0.001	*	0.545		0.834		0.239	
168	All communities	Intended uptake (sandbags)	Threat	Overall flood experience	0.000	*	0.893		0.915		0.310	

Table A-4 continued

	Sample	Z	Y	X	1 Z=aY	2 Z=bX	3 Z = aY + bX vs. Z = aY	4 Y= bX
169	All communities	Post-2012 uptake (warnings)	Self-efficacy (flood warnings)	Flood action group	0.000 *	0.118	0.077	0.662
170	All communities	Post-2012 uptake (warnings)	Self-efficacy (warning)	Flood action group	0.000 *	0.060	0.112	0.225
171	All communities	Intended uptake (warning)	Self-efficacy (flood warnings)	Flood action group	0.000 *	1.000	0.447	0.638
172	All communities	Intended uptake (warning)	Self-efficacy (warning)	Flood action group	0.000 *	0.827	0.884	0.706
173	Communities with a group	Post-2012 uptake (warnings)	Self-efficacy (flood warnings)	Usefulness	0.000 *	0.083	0.635	0.024 *
174	Communities with a group	Post-2012 uptake (warnings)	Self-efficacy (warning)	Usefulness	0.000 *	0.020 *	0.221	0.009 *
175	Communities with a group	Intended uptake (warning)	Self-efficacy (flood warnings)	Usefulness	0.000 *	0.020 *	0.255	0.019 *
176	Communities with a group	Intended uptake (warning)	Self-efficacy (warning)	Usefulness	0.000 *	0.020 *	0.099	0.061
177	Communities with a group	Post-2012 uptake (warnings)	Self-efficacy (flood warnings)	Information on the implementation of measures	0.000 *	0.099	0.992	0.008 *
178	Communities with a group	Post-2012 uptake (warnings)	Self-efficacy (warning)	Information on the implementation of measures	0.000 *	0.053	0.099	0.269
179	Communities with a group	Intended uptake (warning)	Self-efficacy (flood warnings)	Information on the implementation of measures	0.000 *	0.154	0.727	0.013 *
180	Communities with a group	Intended uptake (warning)	Self-efficacy (warning)	Information on the implementation of measures	0.000 *	0.061	0.086	0.360
181	Communities with a group	Post-2012 uptake (warnings)	Self-efficacy (flood warnings)	Information on available measures	0.000 *	0.188	0.941	0.003 *

Table A-4 continued

	Sample	Z	Y	X	1 Z=aY		2 Z=bX		3 Z = aY + bX vs. Z = aY		4 Y= bX	
182	Communities with a group	Post-2012 uptake (warnings)	Self-efficacy (warning)	Information on available measures	0.000	*	0.120		0.210		0.173	
183	Communities with a group	Intended uptake (warning)	Self-efficacy (flood warnings)	Information on available measures	0.000	*	0.070		0.534		0.000	*
184	Communities with a group	Intended uptake (warning)	Self-efficacy (warning)	Information on available measures	0.000	*	0.033	*	0.175		0.081	
185	Communities with a group	Post-2012 uptake (warnings)	Self-efficacy (flood warnings)	Involvement	0.000	*	0.409		0.901		0.178	
186	Communities with a group	Post-2012 uptake (warnings)	Self-efficacy (warning)	Involvement	0.000	*	0.306		0.357		0.806	
187	Communities with a group	Intended uptake (warning)	Self-efficacy (flood warnings)	Involvement	0.000	*	0.215		0.972		0.138	
188	Communities with a group	Intended uptake (warning)	Self-efficacy (warning)	Involvement	0.000	*	0.312		0.134		0.567	
189	Communities with a group	Post-2012 uptake (warnings)	Self-efficacy (flood warnings)	Information on flood warnings	0.000	*	0.003	*	0.172		0.003	*
190	Communities with a group	Post-2012 uptake (warnings)	Self-efficacy (warning)	Information on flood warnings	0.000	*	0.001	*	0.002	*	0.761	
191	Communities with a group	Intended uptake (warning)	Self-efficacy (flood warnings)	Information on flood warnings	0.000	*	0.010	*	0.533		0.002	*
192	Communities with a group	Intended uptake (warning)	Self-efficacy (warning)	Information on flood warnings	0.000	*	0.007	*	0.004	*	0.829	
193	All communities	Post-2012 uptake (warnings)	Self-efficacy (flood warnings)	Existing schemes	0.000	*	0.033	*	0.657		0.000	*
194	All communities	Post-2012 uptake (warnings)	Self-efficacy (warning)	Existing schemes	0.000	*	0.012	*	0.268		0.000	*

Table A-4 continued

	Sample	Z	Y	X	1 Z=aY	2 Z=bX	3 Z = aY + bX vs. Z = aY	4 Y= bX
195	All communities	Intended uptake (warning)	Self-efficacy (flood warnings)	Existing schemes	0.000 *	0.007 *	0.176	0.004 *
196	All communities	Intended uptake (warning)	Self-efficacy (warning)	Existing schemes	0.000 *	0.003 *	0.056	0.001 *
197	All communities	Post-2012 uptake (warnings)	Self-efficacy (flood warnings)	Pre-2012 flood experience	0.000 *	0.347	0.560	0.444
198	All communities	Post-2012 uptake (warnings)	Self-efficacy (warning)	Pre-2012 flood experience	0.000 *	0.486	0.594	0.671
199	All communities	Intended uptake (warning)	Self-efficacy (flood warnings)	Pre-2012 flood experience	0.000 *	0.901	0.783	0.693
200	All communities	Intended uptake (warning)	Self-efficacy (warning)	Pre-2012 flood experience	0.000 *	0.826	0.670	0.936
201	All communities	Post-2012 uptake (warnings)	Self-efficacy (flood warnings)	Post-2012 flood experience	0.000 *	0.690	0.518	0.507
202	All communities	Post-2012 uptake (warnings)	Self-efficacy (warning)	Post-2012 flood experience	0.000 *	0.836	0.961	0.760
203	All communities	Intended uptake (warning)	Self-efficacy (flood warnings)	Post-2012 flood experience	0.000 *	0.470	0.167	0.789
204	All communities	Intended uptake (warning)	Self-efficacy (warning)	Post-2012 flood experience	0.000 *	0.360	0.627	0.299
205	All communities	Post-2012 uptake (warnings)	Self-efficacy (flood warnings)	Average flood experience	0.000 *	0.850	0.447	0.675
206	All communities	Post-2012 uptake (warnings)	Self-efficacy (warning)	Average flood experience	0.000 *	0.657	0.512	0.953
207	All communities	Intended uptake (warning)	Self-efficacy (flood warnings)	Average flood experience	0.000 *	0.095	0.022 *	0.731

Table A-4 continued

	Sample	Z	Y	X	1 Z=aY		2 Z=bX	3 Z = aY + bX vs. Z = aY		4 Y= bX	
208	All communities	Intended uptake (warning)	Self-efficacy (warning)	Average flood experience	0.000	*	0.055	0.097		0.330	
209	All communities	Post-2012 uptake (warnings)	Self-efficacy (flood warnings)	Overall flood experience	0.000	*	0.570	0.900		0.417	
210	All communities	Post-2012 uptake (warnings)	Self-efficacy (warning)	Overall flood experience	0.000	*	0.728	0.813		0.908	
211	All communities	Intended uptake (warning)	Self-efficacy (flood warnings)	Overall flood experience	0.000	*	0.971	0.462		0.654	
212	All communities	Intended uptake (warning)	Self-efficacy (warning)	Overall flood experience	0.000	*	0.708	0.627		0.707	
213	All communities	Post-2012 uptake (warnings)	Risk	Pre-2012 flood experience	0.066		0.360	0.318		0.970	
214	All communities	Intended uptake (warning)	Risk	Pre-2012 flood experience	0.000	*	0.935	0.913		0.795	
215	All communities	Post-2012 uptake (warnings)	Risk	Post-2012 flood experience	0.050	*	0.415	0.043	*	0.000	*
216	All communities	Intended uptake (warning)	Risk	Post-2012 flood experience	0.001	*	0.298	0.319		0.000	*
217	All communities	Post-2012 uptake (warnings)	Risk	Average flood experience	0.056		0.883	0.308		0.000	*
218	All communities	Intended uptake (warning)	Risk	Average flood experience	0.000	*	0.073	0.867		0.000	*
219	All communities	Post-2012 uptake (warnings)	Risk	Overall flood experience	0.066		0.615	0.463		0.410	
220	All communities	Intended uptake (warning)	Risk	Overall flood experience	0.000	*	0.943	0.986		0.532	

Table A-4 continued

	Sample	Z	Y	X	1 Z=aY		2 Z=bX	3 Z = aY + bX vs. Z = aY	4 Y= bX	
221	All communities	Post-2012 uptake (warnings)	Threat	Pre-2012 flood experience	0.435		0.360	0.334	0.621	
222	All communities	Intended uptake (warning)	Threat	Pre-2012 flood experience	0.014	*	0.935	0.989	0.689	
223	All communities	Post-2012 uptake (warnings)	Threat	Post-2012 flood experience	0.522		0.415	0.248	0.000	*
224	All communities	Intended uptake (warning)	Threat	Post-2012 flood experience	0.053		0.298	0.790	0.000	*
225	All communities	Post-2012 uptake (warnings)	Threat	Average flood experience	0.410		0.883	0.656	0.001	*
226	All communities	Intended uptake (warning)	Threat	Average flood experience	0.009	*	0.073	0.329	0.000	*
227	All communities	Post-2012 uptake (warnings)	Threat	Overall flood experience	0.435		0.615	0.542	0.332	
228	All communities	Intended uptake (warning)	Threat	Overall flood experience	0.014	*	0.943	0.991	0.365	

(*), p<0.05 based on Likelihood Ratio tests

Table A-4 continued

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Surveys

A survey of decision-making approaches for climate change adaptation: Are robust methods the way forward?

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ABSTRACT

Applying standard decision-making processes such as cost–benefit analysis in an area of high uncertainty such as climate change adaptation is challenging. While the costs of adaptation might be observable and immediate, the benefits are often uncertain. The limitations of traditional decision-making processes in the context of adaptation decisions are recognised, and so-called robust approaches are increasingly explored in the literature. Robust approaches select projects that meet their purpose across a variety of futures by integrating a wide range of climate scenarios, and are thus particularly suited for deep uncertainty. We review real option analysis, portfolio analysis, robust-decision making and no/low regret options as well as reduced decision-making time horizons, describing the underlying concepts and highlighting a number of applications. We discuss the limitations of robust decision-making processes to identify which ones may prove most promising as adaptation planning becomes increasingly critical; namely those that provide a compromise between a meaningful analysis and simple implementation. We introduce a simple framework identifying which method is suited for which application. We conclude that the 'robust decision making' method offers the most potential in adaptation appraisal as it can be applied with various degrees of complexity and to a wide range of options.

1. Introduction

Climate change adaptation research has progressed significantly in the last decade, illuminating many different aspects in the field, including identifying potential adaptation options (Iglesias et al., 2012), exploring impacts under different scenarios (Stern, 2007) and identifying relevant governance challenges in policy decisions (Huntjens et al., 2012; Pahl-Wostl, 2009). But relatively few adaptation actions have actually been implemented (Wise et al., in press). At the same time, climate change projections highlight the likelihood that humankind will have to prepare for severe changes: the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2013) indicates that warming trajectories of global temperature will likely exceed two degrees by 2100 and a World Bank report (Worldbank, 2012) projects that the planet is on track for a four degree Celsius warmer world by 2100. These reports go beyond the conceptualisation of climate change adaptation, making an emphatic call for adaptation actions in the present. Adaptation in many sectors will be reactive as the time frame for many decisions is too short to take into consideration the long-term climate signal. Adjusting growing seasons in agriculture according to changes in climatic conditions is a classic example. A farmer can implement such changes on a yearly or seasonal basis observing the prevailing weather. But implementing such incremental adaptations may not be sufficient in the long term, when anticipatory and planned adaptation is required; for example large infrastructure projects with long life times such as urban drainage structures, dams or sea walls. In some cases, society will want to avoid threshold events, such as the extinction of certain species. Moreover, extreme events may become more frequent and intense with climate change (IPCC, 2012), which may also necessitate intervention now. Where anticipatory adaptation leads to a situation in which the system is over- or under-adapted to the future climate outcome, additional costs are incurred either through large residual climate change impacts, the waste of investment if changes are not as severe as projected, or through the failure to seize new opportunities arising from climate change. Fankhauser (2009) reviewed different studies of adaptation costs whose estimates range from around $25 billion a year to well over $100 billion for the next 20 years based on 'median' climate change. Considering that the impacts of climate change might only become more severe in the more distant future, these costs may be an underestimation, but also show the inherent uncertainty of the costs of adaptation. In the context of a global economic crisis that is only slowly receding, a fortiori the allocation of significant resources to adaptation needs to be carefully scrutinised to invest wisely in appropriate options. Economists strive to give investment recommendations that minimise costs and maximise benefits. In other words, to allocate resources optimally by finding the strategy that is better than any other alternative for a given situation. Decision makers largely still use traditional economic analysis techniques for appraising

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adaptation investments, predominantly cost–benefit analysis (CBA), which struggles to account for uncertainty. Methods that extend these tools are increasingly being discussed but applications remain relatively scarce. In this paper, we progress the existing literature on these techniques by providing a decision-making framework to guide decision makers to the most appropriate appraisal method for their situation. We also indicate which robust methods may prove most promising as adaptation planning becomes increasingly critical.

We first summarise traditional decision-making approaches to appraise investment, describing briefly cost–benefit analysis, cost–effectiveness analysis and multi-criteria analysis, followed by the difficulties of applying these methods in the context of climate uncertainty. Section 3 then presents the conceptual basis of decision-making approaches that deal better with uncertainty, so-called robust methods. The overview is not exhaustive: it describes the methods and tools that are currently most discussed in the adaptation literature and in other taxonomies of decision-support approaches (Hallegatte et al., 2012; Herman et al., 2014; Jones et al., 2014; Kunreuther et al., 2014). We focus in particular on the underlying assumptions of these methods and on the conditions under which the methods work well, and illustrate each method with a number of applications from the literature. Subsequently, we provide a simple framework summarising which adaptation problem is best appraised by which decision-making process. In Section 4, we extend the discussion on robust methods by describing the limitations of robust decision-making methods, reflecting on why they have so far not been more widely applied in real projects. Finally, we outline the potential future direction of research for robust methods, identifying which may prove most promising for policy making; namely those that find a compromise between a meaningful analysis and simple implementation.

2. Traditional decision-making approaches

Cost–benefit analysis, cost–effectiveness analysis and multi-criteria analysis are widely used decision-making approaches in policy analysis when appraising projects.

Cost–benefit analysis (CBA) attempts to maximise the benefits for society based on potential Pareto efficiency.[1] It assesses whether it is worthwhile to implement a project by comparing *all* its monetised costs and benefits expressed over a defined time span to obtain its net present value (NPV) as in Eq. (1):

$$\mathrm{NPV}(i, N) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t} \tag{1}$$

where N is the total number of periods, i the discount rate, t is time and R_t is the net benefits (benefits minus cost) at time t. For CBA in adaptation, climate change impacts and their value must first be estimated. For this, climate projections from coupled ocean/atmosphere general circulation models (OA/GCMs) under a range of greenhouse gas emission scenarios are downscaled. This output is then fed into impact models to determine for example changes in rainfall of or crop yields. Subsequently, the impact following the adaptation option must then also be valued, and the difference between pre- and post-adaptation impacts provides the net benefits of adaptation R_t. Additionally, the costs of adaptation must be estimated over this time period. Fig. 1 illustrates how adaptation benefits are obtained.

The stream of benefits and costs over time is discounted to present values, and a net present value (NPV) is calculated by subtracting the net costs (cost of adaptation measure) from the net benefits (pre-adaptation minus post-adaptation impacts, thus avoided damages). A positive NPV indicates that the project should generally proceed (Boardman et al., 2014). Alternatively, if the ratio of benefits to costs ("benefit–cost ratio") is larger than one, the investment is economically desirable. Provided that reliable data on costs and benefits are available, CBA can be carried out with limited technical resources and the results are accessible to a non-technical audience (for applications, see for example Escobar (2011) and Willenbockel (2011)).

Cost–effectiveness analysis (CEA) represents an alternative to cost–benefit analysis when it is difficult or controversial to monetise benefits, such as the value of lives saved or landscape values. CEA compares mutually exclusive alternatives in terms of the ratios of their costs and a single quantified, non-monetised effectiveness measure with the aim to choose the least cost option. CEA is relatively straightforward in terms of optimisation: when effectiveness across all options is assumed to be identical it amounts to a simple cost minimisation problem such as achieving an acceptable level of flood protection. When the budget is fixed, an effectiveness maximisation problem is solved. For applications to adaptation, see for example Boyd et al. (2006) and Luz et al. (2011).

CEA works best if the benefits of the adaptation options are identical given one metric. This might apply with regard to clearly defined technical solutions. But if neither costs nor benefits are identical, scale effects need to be considered: policies with low impact at a relatively low cost per unit will be ranked higher than policies that have high impacts at a somewhat higher cost (Boardman et al., 2014) (see also Kunreuther et al. (2014) for further comparison of CBA and CEA in the context of climate policy).

Multi-criteria analysis (MCA) in its simplest application (whose complexity can be increased in various ways) usually consists of a combination of quantitative and qualitative (monetised and non-monetised) indicators that provides a ranking of alternatives based on the weight the decision maker gives to the different indicators (see for example Garcia de Jalon et al. (2013) for an application). For example, distributional or psychological impacts for which it is difficult to assign a monetary value can be integrated according to the preferences of the decision maker. Results from other methods such as cost–benefit analysis can be included (UNFCC, 2009). Through the weighting, the data is mapped onto an ordinal scale and both quantitative and qualitative data can be compared relatively, but not with regard to an absolute scale, prohibiting a generalisation of the results.

CBA, CEA and MCA have all long been tested, further developed and successfully applied to many projects and policies, but policy makers face considerable challenges when applying these decision-making approaches in an area of uncertainty such as climate change adaptation. While the costs might be observable and immediate, the benefits of adaptation are harder to define, as these require planning and foresight about how the climate will change. Indeed, there is considerable uncertainty attached to climate change projections, as well as to the expected impacts and responses to them (Dessai and van der Sluijs, 2007). In particular, uncertainty exists with regard to downscaled climate data such as localised data on precipitation, temperature and flood probabilities, which might not be resolved for a long time, if at all (Fankhauser and Soare, 2013). Uncertainty also stems from the future emissions of GHG, how global and local climate systems will react to these changes in emissions as well as the response of other systems to climate change, including ecosystems (Wilby and Dessai, 2010). Finally, there is uncertainty regarding knock-on effects on society and the economy depending on their vulnerability and adaptive capacity (Kunreuther et al., 2012).

These unknowns make the application of the decision-making approaches described above at least in their 'basic' formulation challenging. The uncertainty can be addressed in different ways. For example, an expected values framework attaches "subjective probabilities" (Hallegatte et al., 2012), to evaluate the expected benefits as the probability-weighted average of the benefits based on how likely different states of the world are (Gilboa, 2009). Probabilities can be based on past occurrences of events, expert knowledge, or both. Subsequently projects matching the conditions of that future are designed and fine-tuned with sensitivity analysis. Similar to this is expected utility—if

[1] An allocation is pareto efficient if no alternative allocation can make at least one person better off without making anyone else worse off.

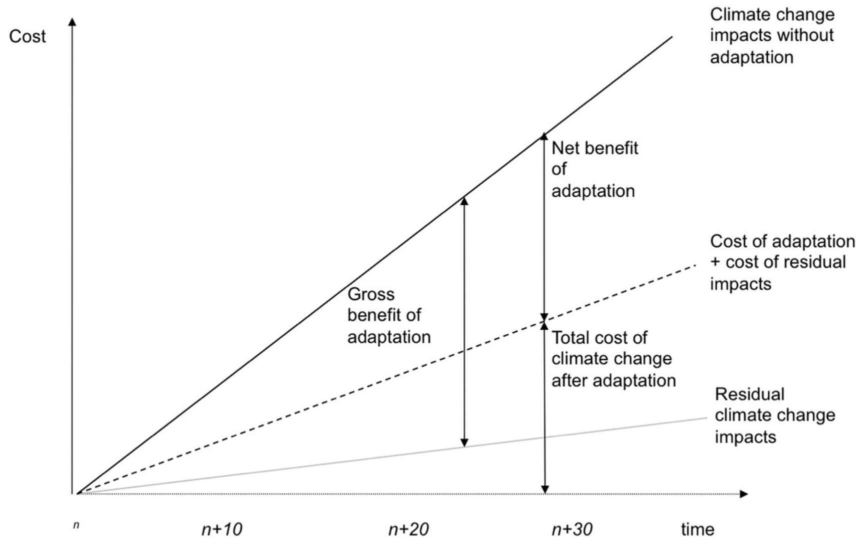

Fig. 1. Costs and benefits of adaptation.

the risk preferences of those affected are known (Watkiss et al., 2014). This approach is variously labelled as 'science first' (Ranger et al., 2010), 'top-down approach' (Wilby and Dessai, 2010) or 'agree-on-assumptions' (Kalra et al., 2014) in the context of adaptation. Additionally, scenarios of how the future might unfold (of equal likelihood) can be used (Boyd et al., 2006; Garcia de Jalon et al., 2013); for CBA this is a variant to include more than the central estimate as in the expected value framework. Worst- and best cases that might be of particular interest in the context of climate change can be easily turned into scenarios. Related to this is the min/max approach that aims to minimize the possible loss for a worst case (maximum loss) scenario for prudency. Put differently, we choose the alternative such that its lowest possible expected value (i.e., lowest according to any possible probability distribution) is as high as possible (maximize the minimal expected value) (Von Neumann, 1967). Reliability-weighted expected value calculates the weighted average of probabilities, giving to each probability the weight assigned by its degree of reliability (Howard, 1988). Further variations of decisions under uncertainty exist (see Hansson (2005) for an overview) which all rely on attaching subjective probabilities to different outcomes.

All of these strategies have associated difficulties. Using several climate change scenarios provides the end-user with a range of possible outcomes, but with no attached probabilities making it difficult to make an informed decision (New and Hulme, 2010). Expected values can be used in situations of quantifiable uncertainty. But for climate change we do not have a strong methodology to assess these subjective probabilities. They cannot be fully based on the past, because climate change is a new process for which we have no historical equivalent. Models share common flaws in their assumptions and their dispersion in results cannot be used to assess the real uncertainty (Hallegatte et al., 2012). The term deep uncertainty (Lempert et al., 2003) or severe uncertainty is used (Ben-Haim, 2006) in these contexts. Such uncertainty is characterised as a condition where decision makers do not know or cannot agree upon a model that adequately describes cause and effect or its key parameters (Walker et al., 2012). This leads to a situation where it is not possible to say with confidence whether one future state of the world is more plausible than another. Also, challenges can arise if there is disagreement on the ethical judgment and worldviews as objectives need to be agreed upon (based on a decision criterion) (Hallegatte et al., 2012).

The limitations of traditional decision-making approaches for investment appraisal in the context of climate change have been recognised by many decision makers and governments. Alternative decision making approaches to appraise and select adaptation options are therefore being explored, both in the academic and policy literature (Dessai and Sluijs van de, 2007; European Commission, 2013; Hallegatte and Corfee-Morlot, 2011; Hallegatte et al., 2012; Ranger et al., 2010; UNFCC, 2009). The aim is to better incorporate uncertainty while still delivering adaptation goals, by selecting projects that meet their purpose across a variety of plausible futures (Hallegatte et al., 2012); so-called robust decision-making approaches. These are designed to be less sensitive to uncertainty about the future and are thus particularly suited for deep uncertainty (Lempert and Schlesinger, 2000). Instead of optimising for one specific scenario, optimisation is obtained across scenarios: robust approaches do not assume a single climate change forecast, but integrate a wide range of climate scenarios through different mechanisms to capture as much of the uncertainty on future climates as possible. This is achieved in different ways: by finding the least vulnerable strategy across scenarios (robust decision making), defining flexible, adjustable strategies (real option analysis) or by diversifying adaptation options to reduce overall risk (portfolio analysis). Furthermore, no or low regret options that perform well independent of the climate driver are also discussed in the context of robust methods, although they are not decision-making approaches per se but options.

For risk-averse decision makers, robust strategies are attractive as they help to reduce the range of uncertainty in an investment decision. They can thus help to reach consensus on actions as different future scenarios and thus diverging viewpoints are better integrated, while reducing the risk of over- and under-adaptation. But different adaptation problems will require different techniques depending on the characteristics of the adaptation options and the nature of the uncertainty. While much discussed in the academic literature (Dessai and Sluijs van de, 2007; Hallegatte and Corfee-Morlot, 2011; Hallegatte et al., 2012; Lempert and Schlesinger, 2000; Ranger et al., 2010; Watkiss et al., 2009; Wreford et al., 2010) and in policy documents (Frontier Economics, 2013; UNFCC, 2009) so far relatively few applications exist.

3. Robust decision-making approaches

3.1. Portfolio analysis

Portfolio analysis (PA) is akin to combining shares in a portfolio to reduce risk by diversification (Markowitz, 1952). Analogously, a basket of adaptation options is determined by maximising adaptation returns given the decision maker's risk affinity. Alternatively, given a defined return of the adaptation options, risk is minimised across all adaptation options for different climate change scenarios. A portfolio is best balanced if the co-variance of the assets is negatively related, off-setting the risk under different scenarios. In other words, a low return on one asset will be partly offset by higher returns from other assets during the same period. For example, solving for minimising risk for different target returns will provide a range of feasible portfolios specifying the weights (quantity) of the different adaptation options in each portfolio. The benefits can be expressed both in monetary and non-monetary terms, for instance as conservation values of wetland habitats (Ando and Mallory, 2012), or as the potential to regenerate forests with different tree seeds (Crowe and Parker, 2008). Fig. 2 shows different feasible portfolios for different target returns on an efficient frontier. In the application of Ando and Mallory (2012), the benefit axis refers to the average expected value of conservation of land while the risk axis expresses the standard deviation of the conservation values. Thus the decision maker can make an explicit choice between average expected value of return and riskiness (standard deviation of the return); the higher the risk, the higher the expected value.

PA thus allows a trade-off between the return and the uncertainty of the return of different combinations of adaptation options under alternative climate change projections. However PA still requires assumptions about probabilities of plausible climate change scenarios and associated impacts, and is thus still a ‘predict-then act’ decision-making process. The method also only works if the returns of the adaptation options are negatively correlated and their correlation can be well specified for a long term planning horizon. This might for example be a basket of locations where certain animal or plant species may be preserved.

The strict application criteria may account for the limited number of applications, which to date are focused in the area of conservation (Ando and Mallory, 2012; Crowe and Parker, 2008). But the technical requirements are not necessarily complex and returns may include both economic efficiency and physical effectiveness, so it would be worth exploring further applications. In the area of conservation management in particular, costs will often be quantifiable but benefits are likely to be much more difficult and controversial to measure. This is for example the case for ecosystem services of peatlands or forests where so far hardly any estimates exist (Moran et al., 2013) and might therefore be well suited for an application of portfolio analysis.

3.2. Real option analysis

Flexible and reversible approaches handle deep uncertainty by allowing for learning about climate change over time, and are designed in a way that they can be adjusted or reversed over time when additional information becomes available. Real options analysis (ROA) is one of the several ways to formalize policies that adapt over time in response to new information.

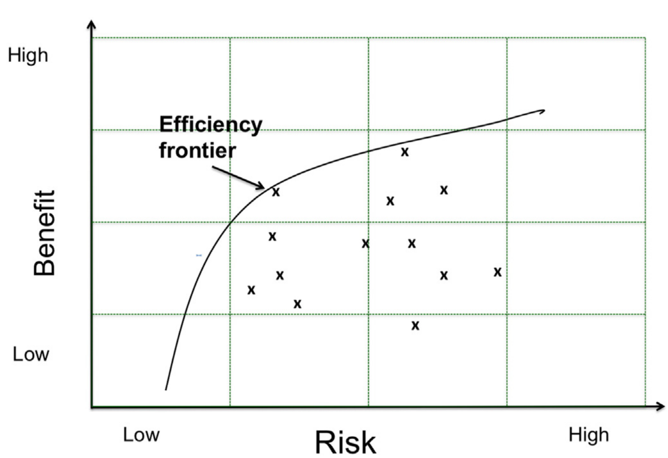

Fig. 2. Efficiency frontier: a portfolio on the frontier is chosen according to risk preference.

Real option analysis (ROA) originates from financial economics (Cox et al., 2002; Dixit and Pindyck, 1994; Merton, 1973) and extends the principles of cost–benefit analysis to allow for learning based on an uncertain underlying parameter.

The uncertain parameter in the context of climate change is a specific climate variable: rainfall, temperature or sea level rise, for example. ROA analyses whether it is worth waiting for more information, i.e. it estimates the value of additional information given the uncertainty surrounding climate change, instead of possibly over- or underinvesting now. Thus, there is a trade-off between obtaining the potential pay-off in the present and waiting for further scientific information in the future (Gollier and Treich, 2003).

ROA relies on the assumption that uncertainty is dynamic rather than deep. Uncertainty is assumed to resolve to a degree with the passage of time due to increasing knowledge on climate change impacts. The idea can be illustrated in a simple decision tree as in Fig. 3.

Gersonius et al. (2013) applied this strategy to urban drainage infrastructure in West Garforth, England: the connecting lines in the decision tree in Fig. 3 depict the change in the climate variable rainfall intensity either upwards, downwards or remaining the same over a period of 60 years (divided into 30 year intervals). The decision nodes reflect adaptation options such as replacing sewer conduits or building and upsizing storage facilities. Given these climate paths, ROA looks at each and every possible scenario and indicates what to do in any of these contingent events, i.e. which adaptation option to implement. Thus, the strategy is adjustable and a specific implementation is chosen by observing the actual change of rainfall intensity over time. The aim may for example be to minimise the life-time cost or maximise the life time benefit of the specific project. Project A is the initial adaptation option and investment C should be implemented after a period of 30 years, if the climate variable turns out to follow the upward path. Subsequently a set of further projects can be implemented approaching the end of the second period. The optimal choice made during the second period is determined by the choice made in the first period. Thus, an adaptation strategy is developed that can be adjusted if needed when reassessing the strategy in 30 years and again in 60 years as different plausible scenarios will have been considered today.

ROA works particularly well for large irreversible investments with long life times and sensitivity to climate conditions, when there is a significant chance of over- or underinvesting combined with an opportunity cost to waiting, i.e. if there is a need for action in the present. It has a timeliness and a flexibility implication: first, ROA evaluates the benefits of postponing part or all of an (irreversible) investment, and second, it can assess technical options created or destroyed through the project (Wang and De Neufville, 2005).

Regarding the timing of the investment, the larger the cost of the immediate investment, the more the valuation is skewed towards postponing the investment and vice versa. Thus, if there are ancillary benefits to the adaptation strategy independent of the uncertain underlying parameter (climate risk), for example in the case of natural flood risk measures that may provide significant ecosystem services independent of the climate factor flood risk, waiting may not be worthwhile.

In terms of the technical flexibility of an investment, a flexible ‘real option’ strategy that can be adjusted over time will often be more expensive initially than a supposedly optimal single solution. But the latter might become more costly if the climate change impacts turn out differently than expected leading to premature scrapping or expensive retrofitting (Ranger et al., 2010). Unlike traditional appraisal methods, ROA does not result in a single highest ranked option as an output. It provides flexible strategies along the different climate paths that can be adjusted over time and an explicit valuation of created and destroyed capabilities (Hallegatte et al., 2012).

While relatively widely used for investment projects in the business world (Copeland and Tufano, 2004), there are few applications in climate change adaptation. These include mainly large infrastructure flood protection projects such investment in coastal protection

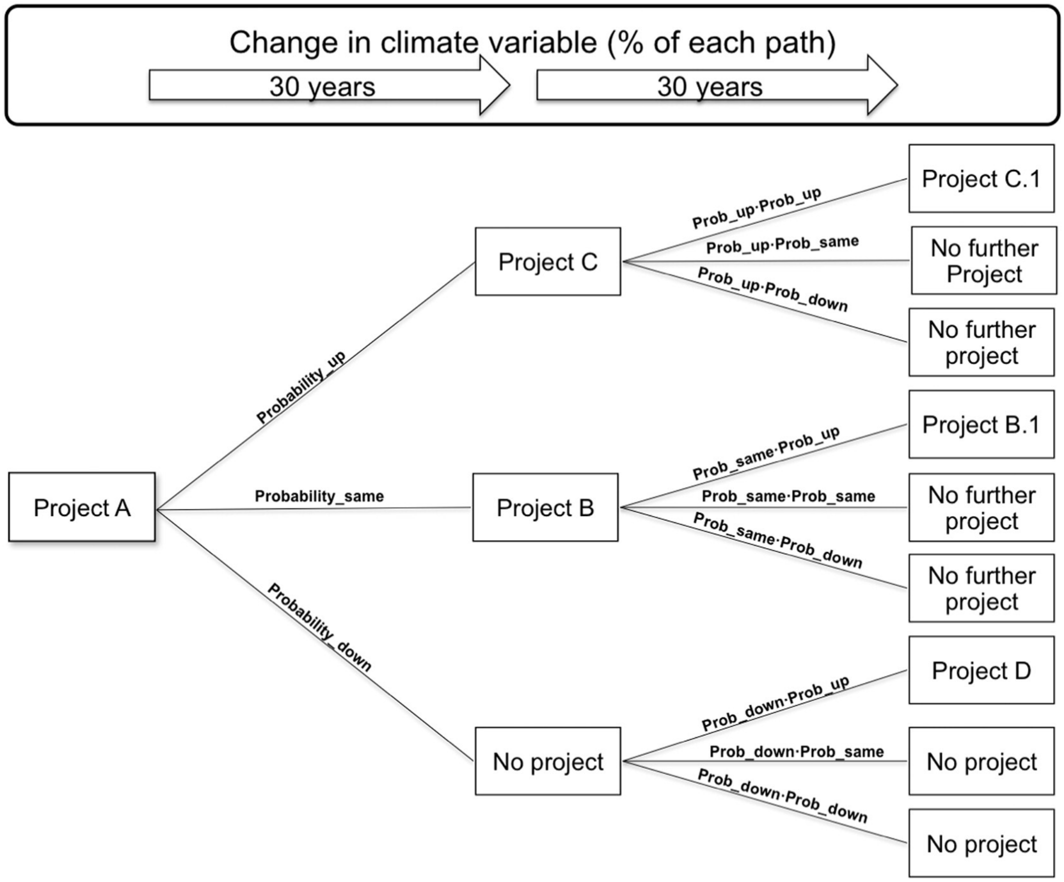

Fig. 3. Real option decision tree.

(Linquiti and Vonortas, 2012; Scandizzo, 2011; Woodward et al., 2011). Gersonius et al. (2013) investigated the added value of real option analysis with regard to investments in urban drainage infrastructure in West Garforth, England. The strategy is adjustable and a specific implementation is chosen by observing the actual change of rainfall intensity over time. Other closely related decision-making approaches to ROA include the dynamic adaptive pathways work (Haasnoot et al., 2013), adaptive policy-making (Walker et al., 2001) as well as adaptation tipping points (Kwadijk et al., 2010) and adaptation pathways (Haasnoot et al., 2011, 2012). They vary in terms of how they identify different climate paths, trigger points for action and design plans that can be adjusted as well as how they are presented visually.

Limited application may be related to the complexity of the appraisal process. Probabilities need to be assigned to different plausible climate change paths assuming a science-first approach. However, probabilistic data may not be available for all regions as it is for example for the UK (Murphy et al., 2009) and these depend on different emissions scenarios. Additionally, to provide quantitative results, good data is necessary: methods such as genetic algorithms or dynamic programming that usually require expert knowledge can provide solutions to the objective function. However, ROA can also be applied qualitatively by drawing up a decision tree that outlines different adaptation paths to provide conceptual guidance on the adaptation strategy. Moreover, the short term nature of decision making and budgeting both in the public and private sectors works against the implementation of such long term plans with possible high up-front costs.

3.3. Robust-decision making

A policy-first (Carter et al., 2001), or also called 'vulnerability-first', 'thresholds first' (IPCC, 2012), or 'context first' approach (Ranger et al., 2010) is based on the principle of first defining the objectives and constraints of the adaptation problem and its remedies. In a second step their functioning against different future projections is tested to determine the least vulnerable strategy, such as in robust decision making (RDM).

The concept of robust decision making is not new (Matalas and Fiering, 1977) and has been used in different variations but it is most prominently linked to the RAND Corporation (Lempert et al., 2003). It was originally designed for decision-making in poorly-characterised uncertainty with a subsequent application to climate change adaptation (Lempert et al., 2006). The approach identifies measures that have little sensitivity to different climate change scenarios by trading off some optimality (Lempert and Collins, 2007). Fig. 4 illustrates the decision-making process of RDM.

First, the problem at hand is structured, i.e. what is the aim of the decision-making process, and subsequently a number of potential strategies are identified. In an application of Lempert and Groves (2010) the current water management plan in the Western U.S. that aims to ensure sufficient and affordable water supply was tested. Possible management options included recycling of water, improved water efficiency and expansion of ground water. It is crucial that the uncertain parameters and their plausible ranges are identified, as these will define the vulnerability of different strategies. For the case study, beside a wide range of climate change scenarios, future socioeconomic conditions, the agency's ability to implement the plan and costs went into the analysis based on climate change projections and expert knowledge for management options. Simulation models are used to create large ensembles (thousands or millions of runs) of multiple plausible future scenarios from the parameters without assuming a likelihood of the different scenarios. The costs and benefits of different strategies are determined with the use of a value function (Lempert and Schlesinger, 2000; Lempert et al.,

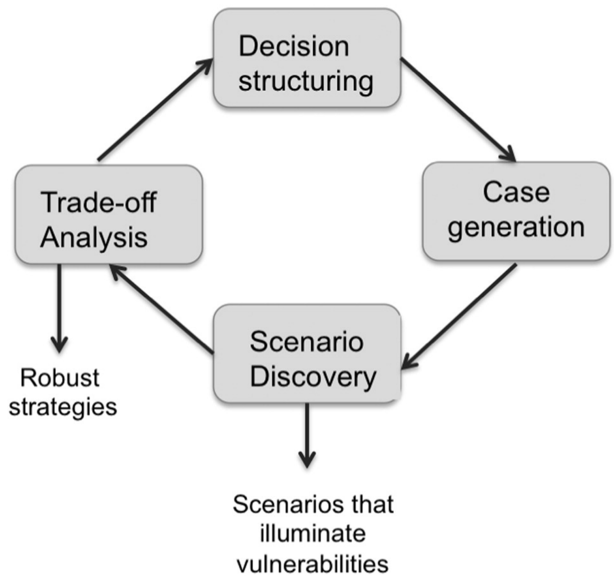

Fig. 4. Conceptualisation of robust decision making (Lempert, 2013).

2006; Lempert and Groves, 2010). Subsequently, the different strategies are tested against a robustness criterion, which may be that the strategy performs well compared with alternative strategies in many different future scenarios, or a certain cost–benefit measure (Lempert and Schlesinger, 2000). For the California study, supply and demand metrics as well as per-unit costs to each of the water supplies (including efficiency) to estimate total costs to the region for consuming and disposing of water were used. In an iterative process, the candidate strategies can be adjusted and fed repeatedly through the ensembles. Accordingly, RDM does not predict uncertainty and then rank alternative strategies, but characterizes uncertainty in the context of a specific decision: the most important combinations of uncertainties to the choice amongst alternative options are determined in different plausible futures. As a result of the analysis, trade-off curves compare alternative strategies rather than providing any conclusive and unique ordering of options. In California, the trade-off curves also included the (political) effort needed to implement certain measures through weights. RDM thus also considers the precautionary principle by illuminating the risks and benefits of different policies (Kunreuther et al., 2014). Generally, a strategy that performs well over a range of plausible futures might be chosen over a strategy that performs optimally under expected conditions. Other approaches closely related to RDM include decision-scaling (Brown and Wilby, 2012) Info-Gap (Ben-Haim, 2006) and many-objective robust decision making (MORDM) (Kasprzyk et al., 2013). They differ in terms of alternative generation, sampling of states of the world, quantification of robustness measures, and sensitivity analysis to identify important uncertainties (see Herman et al., 2014 for further comparison of the approaches). Interestingly, Kasprzyk et al. (2013) conduct a multi-criteria portfolio analysis within a robust decision making context to provide decision support approach. They present pareto surfaces to decision makers and allow them to decide where on the surface they would like to reside. Fig. 2 can be interpreted as a MCA pareto frontier where the return will consist of an array of factors.

RDM applied fully quantitatively is very data and resource intensive. For example, for the development of the water management plan in Southern California an investment of between $100,000 (where a simulation model already exists) and $500,000 (where the model needs to be developed) (Hallegatte et al., 2012) was suggested. The development of the simulation models, the metrics, acceptable risks, the benchmark for testing the strategies, as well as plausible scenarios and their upper and lower bounds need to be clearly defined. Choosing all these parameters implies that assumptions about plausible values need to be made in RDM whose range is up to the decision maker's discretion and may thus introduce a subjective view about the future.

In the literature Groves and Sharon (2013) used RDM to develop a set of coastal risk-reduction and restoration projects in Louisiana, U.S. given a budget constraint. In an application to flood risk management in Ho Chi Minh City's Nhieu Loc-Thi Nghe canal catchment, Lempert et al. (2013) evaluated that the current infrastructure plan may not be the most robust strategy in many plausible futures emphasising the importance of adaptively using retreat measures. A further application includes determining water management strategies such as Lempert and Groves (2010) and Mortazavi-Naeini et al. (2015). The former study tested the current water management plan in the Western U.S. that aims to ensure sufficient and affordable water supply. Besides a wide range of climate change scenarios, future socioeconomic conditions, the agency's ability to implement the plan and costs went into the analysis.

There are some studies that apply RDM in a simplified form, trading off data requirements while retaining the principle of policy first analysis. A study on evaluating natural flood risk measures in North Yorkshire, UK (Frontier Economics, 2013) made an attempt at simplifying robust decision making by reducing the number of climate change scenarios included. Matrosov et al. (2013) use RDM to select portfolios of water supply and demand strategies in the Thames water system, UK, simplifying the methodology by considering a smaller number of options but considering different uncertainties (hydrological flows as well as demand and energy prices). Bonzanigo and Kalra (2014) showed that the data and tools typically used in classic economic analyses such as CBA can be used while applying the principles of RDM with an application to an Electricity Generation Rehabilitation and Restructuring Project to improve Turkey's energy security. Prudhomme et al. (2010) integrated the idea of vulnerability first by testing the sensitivity of catchment responses to a plausible range of climate changes instead of focusing on time-varying outcomes of individual scenarios. This includes scanning over a range of relevant climate parameters to identify the amount of change that would cause a proposed policy to fail which can then be combined with model projections for plausibility (Brown and Wilby, 2012; Groves et al., 2013).

3.4. Robust options by design: no/low regret

A further way of circumventing the difficulty of characterising uncertainty is the generation of alternatives that are robust due to their characteristics irrespective of the approach to appraise them. These options may be an alternative in the short term to handle climate change uncertainty. No regret options (also labelled early benefits (Fankhauser and Soare, 2013)), avoid the necessity of quantifying climate change impacts. Instead these robust options will yield social and/or economic benefits irrespective of whether climate change occurs delivering benefits now and building future resilience (Watkiss and Hunt, 2014). The options are usually specific to the adaption problem. Typical examples include fixing leakages in water pipes or water use efficiency improvements in areas that already suffer from long-run drought and increased demands independent of climate change (Hurd, 2008). With quickly visible benefits, decision makers are likely to implement no regret options more readily in contrast with other less robust adaptations. Indeed, no regret options are often considered best practice and should be implemented in any case as a first step towards increased resilience. Assessing the net benefits of such adaptation options can be carried out with CBA, CEA or MCA.

While the concept of no regret options initially appears relatively uncontroversial, it is unclear what low regret options comprise (Preston et al., 2015). They may have low costs, some benefits now and in the future, or they may be options that lead to future benefits or offer benefits across most climate scenarios (Watkiss and Hunt, 2014). Different (sometimes controversial) examples include building adaptive capacity, such as measures to deal with heat stress in cities and irrigation. However, irrigation may become a maladaptation if too much water is extracted or resources might be wasted if heat stress is overestimated when traditional predict-then-act approaches for appraisal are applied. Watkiss and Hunt (2014) argue that potential low-regret measures need to be framed in an iteratively adaptive way i.e. integrating the idea that we know best about the near future and less about the distant future. For instance, soil and water quality improvement are low regret options handling current climate variability; investing in upgradable infrastructure with respect to medium-term climate change, and on-going research on climate change with respect to the distant future.

3.5. Reduced decision-making time horizons

Another alternative to reduce uncertainty includes the generation of adaptation alternatives with reduced decision-making time horizons. The aim is to be able to adjust the action over time through several short time horizon decisions based on the assumption that this might be less costly than few large long-term decisions. Examples include lower quality and thus cheaper housing in flood prone areas (although this may also be a maladaptation in terms of the wasted resources and energy used). In forestry, shorter rotation species can be chosen to reduce time horizons as neither safety-margins nor reversibility are feasible (Hallegatte et al., 2012). Similarly, some soft options can reduce decision-making time horizons, for example the use of insurance markets to protect against flooding in the short term (UNFCC, 2009). The robustness here lies in the fact that the features of the adaptation options will likely provide benefits in the short term. Shortening the decision time horizon converts deep uncertainty to potentially quantifiable uncertainty that can then be assessed with appraisal methods that aim for optimality. The strategy can then be revised and adjusted in the future when more information might be available about climate change impacts. However, similarly to low regret measures the question of which measures actually fulfil the reduced decision time horizon characteristics arises, and related to this the extent to which traditional appraisal methods can be employed.

3.6. Which method for which situation?

It is clear that that different approaches will work well in different circumstances, depending on the characteristics of the adaptation options being considered, the data available, and the time and skills available to the decision maker.

To help identify the appropriate method for a particular adaptation project, Fig. 5 presents a simple framework encapsulating the mechanisms of robust decision-making approaches, helping to identify which method will perform well contingent on the characteristics of the available options. This framework presupposes that an area of vulnerability and the adaptation question has been clearly framed, whether this relates to investment in adaptive capacity or infrastructure measures. Also, the available data and their format need to be known (Ranger et al., 2010). It should be clear that any chosen adaptation option should not be in conflict with (emissions) mitigation measures (Smith and Olesen, 2010). The framework also reflects that robust decision-making approaches may not always be feasible and traditional appraisal methods may still work best in some situations due to data limitations and the nature of the adaptation options.

To determine the most appropriate method the adaptation options are characterised according to their scale, level of uncertainty and data availability. The questions must be answered with the available adaptation options in mind. Some adaptation options may be suited to two or even three appraisal methods.

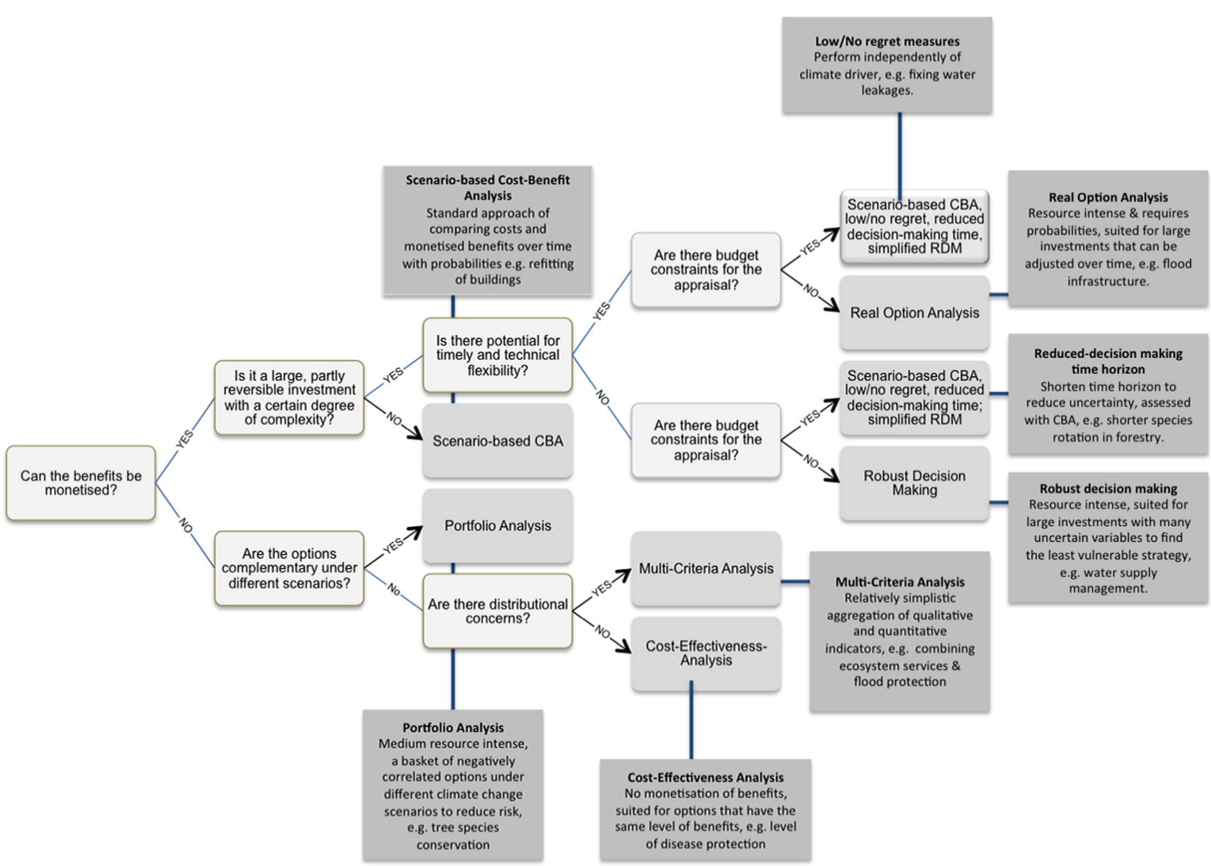

Fig. 5. Finding a suitable appraisal method for adaptation options.
Adapted from DEFRA (2013).

4. Discussion

It is clear that different appraisal methods work well for different adaptation problems. The framework highlights that RDM and ROA, which are relatively resource-demanding might not be feasible if there are budget constraints: either a simplified application of the methods or a traditional appraisal method may need to be used. For example, assuming benefits can be monetised (step 1) but the potential investment is relatively small (or reversible) (step 2), the expenditure for a robust appraisal may not be justified. If the investment is large and (partly) irreversible and timely and technical flexibility exists (step 3), ROA may be suited, provided that there is no major constraint on budget/time for the appraisal (step 4). If this is the case, one may have to revert to one of the less resource intense appraisal approaches (step 5). At the same time, while it is important to choose an appraisal method matching the characteristics of the adaptation options, it is also crucial to recognise that different methods may resonate with different audiences, as they employ different means of communicating decision options and uncertainty. For example, MCA is useful for stakeholder inclusion and can be easily explained to a non-technical audience but the inclusion of climate uncertainties will remain simplistic; whereas, interpreting the results of RDM can be demanding but will provide a comprehensive picture of the various vulnerabilities of strategies. It should be noted that traditional decision-making approaches lead to specific actions that are ought to be implemented based on decision criteria founded in rationality (e.g. highest positive NPV) whereas some of the robust decision-making approaches provide decision support instead (Lempert, 2014). Using the definition from the National Research Council (2009), this represents “the set of processes intended to create the conditions for the production and appropriate use of decision-relevant information.” In particular RDM but also PA focus on the goal of providing actionable information to decision makers, who will then make their own decisions (e.g. trade-offs between options).

Second, despite delivering robust adaptation options and strategies across a range of climate change scenarios, robust methods still require assumptions about climate change scenarios. This seems contradictory at first, as robust methods are designed to handle situations of deep uncertainty (i.e. the absence of reliable data), but for a meaningful analysis it is necessary to clearly specify the range of uncertainties (to the extent this is possible).

ROA and PA are based on predict-then-act, science-first foundations. Both methods require impacts first, usually employing probabilities to describe different but nevertheless limited numbers of climate change scenarios and the adaptation strategy is optimised given the potential climate variability. Both methods then deliver robustness by integrating different climate change scenarios when appraising and simultaneously developing adaptation strategies: ROA by creating adjustable adaptation strategies for different climate change scenarios and PA by implementing a basket of adaptation options suited to different climate change scenarios. Nevertheless, the choice of the climate change scenarios considered and possibly also the probabilities for different climate change outcomes are the subjective decision of the analyst and need to be justified. Similarly, for policy first approaches such as RDM that start out with candidate strategies and not impacts it is still necessary to define the range of climate change risks the strategies are tested against. While considering these different climate change risks can help to explore the scenario space further, it nevertheless implies to an extent a valuation of how extreme the climate changes might turn out to be. Moreover, depending on the concrete adaptation problem at hand considering a very wide band of climate change scenarios can lead to a least vulnerable solution that has low benefits in the climate that actually occurs, as the benefits are considered across scenarios. This point highlights that there is a trade-off between optimality (i.e. choosing a strategy that perfectly matches a certain state of the world) and robustness, and we do not necessarily face a binary choice between an optimal or robust strategy, but rather the objective is to determine the lowest level of trade-off between optimising returns and robustness (Lempert et al., 2003). Weaver et al. (2013) point in this context to the importance of using climate models more intensively and to explore complex systems and their uncertainties. This does not necessarily imply improving projections, which will always suffer from some uncertainty (Dessai et al., 2009), but for example considering a larger set of climate models (Rajagopalan et al., 2009), comparing results from downscaling techniques (Steinschneider et al., 2012), or running a deeper sensitivity analysis to various components in the modelling chain (Dessai and Hulme, 2007), which could ameliorate the use of climate models. The IPCC suggests applying a science-first approach when uncertainties are shallow, and a policy-first approach when uncertainties are deep (Jones et al., 2014).

Third, robust methods are still relatively novel in the academic and policy agenda for adaptation. It is therefore not surprising that planners are as yet unfamiliar with the application of these methods. It takes time to become familiar with new concepts, moving away from traditional appraisal methods. But it is also true that the application of robust methods is in general more complex and time-consuming than carrying out a cost–benefit analysis. Robust methods often require a large amount of (monetised) data and the actual appraisal process might involve relatively complex mechanisms. Examples include the application of genetic algorithms in real option analysis (Gersonius et al., 2013), or solving the value function in robust decision making (Lempert and Groves, 2010). Portfolio analysis requires the specification of standard deviations of the different adaptation options. A simplification of these approaches is needed to make them more accessible to a broader audience. Indeed, real option analysis has already been simplified for its application beyond financial options to real investment projects (Cox et al., 2002) and this could potentially be further developed for adaptation. The development of different flood defence options for the Thames Estuary 2100, England (Environment Agency, 2011) used the principles of real option analysis by applying iterative adaptive management: the plan is flexible to a changing climate because interventions can be brought forward in time, alternative pathways can be included, and existing structures can be extended. While the analysis within the different components was carried out with CBA, the overall project was designed in a flexible way to allow for adjustments. Haasnoot et al. (2013) use the principles of ROA by exploring and sequencing a set of possible adaptations based on external developments in their frameworks of ‘adaptive policymaking’ and ‘adaptation pathways’ as guidance for decision makers.

Similarly, there are some studies that apply robust decision making in a simplified manner as mentioned above (Bonzanigo and Kalra, 2014; Frontier Economics, 2013). Indeed the body of policy first approaches (including RDM) appears to have the greatest potential to become mainstreamed amongst the body of robust methods to decision-making. The principle of starting out with strategies and testing them against uncertainties can be simplified at many points in the analysis. This includes the range of climate scenarios and other uncertainties as well as the number of strategies. While there is also strong academic interest in the other robust decision-making approaches, particularly real option analysis, reflected in the range of studies in this field, it is not obvious that they can be simplified as well as policy-first approaches. Even more importantly, policy-first approaches can be applied well to most adaptation challenges if the options are well differentiated—not necessarily the case for the other approaches.

Despite its advantages however, the application of simplified RDM is also a learning process: from understanding how to structure a robustness analysis, to learning software that aids in scenario discovery, to interpreting the results of scenario discovery, to communicating the idea of trade-offs to stakeholders (Bonzanigo and Kalra, 2014).

In summary, the development of simpler and more generic toolkits for the quantitative application of robust decision-making methods is still in its relative infancy. Thus, the relative size, impacts and risks of the adaptation project need to be taken into account when choosing a decision-making method. While it is doubtlessly worthwhile to apply quantitatively robust methods for long-lived large investments, for example in infrastructure or spatial planning, decision makers might resort to no/low regret measures or reduced decision-making time horizon options where feasible in the short term, which can be assessed with CBA as emerges from Fig. 5.

It should also be clear that robust methods cannot accommodate challenges that are intrinsic to any appraisal method. This includes the question of using an appropriate social discount rate when valuing the benefits accruing for future generations (Pearce and Ulph, 1998) but also the challenge of valuing environmental goods in monetary terms (Garrod and Willis, 1999). More generally all methods are based on incremental changes. Broader questions such as the socio-economic assumptions on which modelling of a distant future should be based or the policy goals of decision makers in the future (Lempert and Groves, 2010; Wise et al., in press) are out of reach for these methods. Certainly, climate change is often only one driver when decision makers consider investment decisions, implying that the costs and benefits need to be studied in a wider context. For example, the demand side is crucial for water supply beyond climate change.

Finally, it should also be noted that further factors may hamper the adaptation option appraisal and ultimately the implementation of adaptation action, including behavioural barriers (Grothmann and Patt, 2005; Adger et al., 2009), the lack of institutional leadership and cooperation (Moser and Ekstrom, 2010), historical path dependency (Abel et al., 2011), or the lack of financial and human resources to implement adaptation actions (Bryan et al., 2009; Kabubo-Mariara, 2009) amongst others.

5. Conclusion

Where planned adaptation to climate change is necessary, decision makers need to move away from striving for solutions that assume that an investment today will necessarily match the actual state in the future. Uncertainties surrounding climate change projections and impacts, as well as changes in emissions in the future, mean that these assumptions will be invalid. Taking these uncertainties on board, decision-makers should consider more robust decision-making methods instead of standard cost–benefit analysis, cost–effectiveness analysis or multi-criteria analysis. Robust approaches do not assume a single climate change projection, but integrate a wide range of climate scenarios through different mechanisms to capture as much as possible the uncertainty on future climates. We have presented a range of robust methods, describing their characteristics, applications and limitations: while providing performance across a range of climate change scenarios, they may yield lower overall performance if compared with the alternative strategy under the actual climate outturn, and a well-defined scenario space is indispensable. Moreover, decision makers need to balance the resources required for employing the methods with the added value they can offer. The body of policy first approaches appears to have the greatest potential to be mainstreamed. They can be simplified at many points in the analyses and applied to a wide range of adaptation problems. Academia has an important role to play in this by further improving the accessibility and demonstrating the general applicability of these methods, and by developing more generic toolkits.

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The impact of flood action groups on the uptake of flood management measures

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Abstract Household flood management measures can significantly reduce the risk from flooding. Understanding the factors that influence the uptake of measures has important implications for the design of measures to induce people to take charge of risk mitigation. We investigate the impact of flood action groups in communities in Scotland on the uptake of four measures: insurance, flood warnings, sandbags and floodgates applying regression analysis using a cross-sectional survey (n = 124). The groups were formed in response to the threat from flooding in those communities, and offer information and training on household flood management measures. We use the theoretical framework of Protection Motivation Theory, and compare uptake of the measures before and after the foundation of the flood action groups, as well as in the near future. The models show positive adoption effects for flood warnings, floodgates and to an extent for insurance, and a positive correlation with increased confidence of implementing and belief in the effectiveness of the measures. The effect is significant if specific information on the measures was provided, indicating the importance of

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tailored content. We conclude that appropriately designed flood action groups can be a cost-effective way of increasing the uptake of household flood management measures.

1 Introduction

In Europe, storms and flooding are the most costly weather-related disasters, accounting for 77 % (€282bn in 2005 value) of economic losses due to extreme weather events between 1980 and 2006 (CEA 2007). Beyond the economic losses, the recovery stage for flood victims often has important repercussions on family, health and work situations. Climate change may increase the frequency of high impact events locally in the future (IPCC 2012) and this may be exacerbated by development of housing in flood-prone areas (Bouwer et al. 2010) as well as impermeable surfaces such as streets and parking lots that increase runoff (Brattebo and Booth 2003). Taking the described factors together, implementing adaptation measures against flooding should be considered in vulnerable areas. This may require public flood protection - for example through integrated flood management strategies on a national and international level (European Union 2007, Scottish Government 2009) - but also adaptation measures implemented by households and firms where flood risk cannot be eliminated due to budget limitations. Private flood protection measures can reduce flood damage significantly (ICPR 2002, Kreibich et al. 2005), depending on the local conditions and the flood severity (Kreibich et al. 2015).

Yet practical experience suggests that households do not necessarily implement adaptation measures in order to increase their resilience to flooding (Kunreuther 1996, Peek and Mileti 2002, Bichard and Kazmierczak 2012). Research addressing household decision-making on flood prevention provides limited insights into the communication of flood risk (Dawson et al. 2011, Meyer et al. 2012, Kellens et al. 2013). There are an increasing number of studies highlighting the role of psychological factors in private adaptation to flooding in addition to risk perception and socio-economic variables. One approach, known as Protection Motivation Theory (PMT), attempts to reflect the main cognitive processes leading to the motivation to take protective action.

PMT suggests that individuals' decisions to take action is influenced not only by their evaluation of the physical risk, but also by their beliefs regarding the cost and effectiveness of the measure, as well as their confidence in implementing it. Several studies have found PMT a suitable framework for exploring flood adaptation behaviour (Grothmann and Reusswig 2006, Zaalberg et al. 2009, Bubeck et al. 2012b, Bubeck et al. 2013, Le Dang et al. 2014).

This study uses insights from PMT to explore the factors influencing the uptake of a range of household flood adaptation measures among 124 private households in Scotland. We add to the existing research by investigating the effect of flood action groups on uptake. These autonomous groups were founded in 2012 in small communities across Scotland with the aim of finding local solutions to flood risk, and provide information and training on a number of flood-related issues. The flood action groups are self-relying and run by community members. We specifically explore whether the groups have a direct impact on uptake and on people's perceptions of the effectiveness of measures and their confidence in implementing them - which according to PMT play an important role in determining flood adaptation behaviour. Thus, if the existence of flood action groups is shown to influence adaptation behaviour, this may indicate an effective, low-cost and relatively simple way to promote private flood adaptation.

The remainder of the article is structured as follows. Section 2 reviews the theoretical framework and relevant literature. Section 3 describes the data and the statistical model. The results are presented in Section 4 followed by a discussion of the practical implications for encouraging households to implement private flood management measures.

2 Protection motivation theory and literature review

PMT (Rogers 1975, Rogers 1983) was originally developed for protective behaviour to health threats and has been successfully extended to other threats including natural hazards such as flooding.

The model distinguishes two cognitive steps to describe the decision process when individuals evaluate a threat and possible coping measures: 'threat appraisal' and 'coping appraisal'. The former includes perceived risk and fear and describes how threatened the individual feels by a specific danger. Coping appraisal focuses on possible responses to address the risk and can be divided into three components. (Rogers and Prentice-Dunn 1997). First, 'response-efficacy' expresses how effectively the individual perceives the measure to reduce risk. 'Self-efficacy' describes whether the individual feels capable and confident to carry out the measure. Finally, 'response cost' refers to both the financial as well as the emotional cost of implementing the measure. Taken together, coping appraisal and threat appraisal influence the protection motivation of an individual, which is considered as the variable to induce, sustain and direct the activity of the individual to protect themselves (Maddux and Rogers 1983). The responses can be both protective and non-protective.

Protective responses are those that reduce the threat and will be enacted if high risk perceptions coincide with a strong coping appraisal. The answers respondents give may be non-protective if high risk perceptions go together with low coping appraisals (Rippetoe and Rogers 1987). Non-protective answers include wishful thinking, avoidance and denial.

Several empirical studies support the applicability of PMT to flooding: Grothmann and Reusswig (2006) applied PMT to flood adaptation behaviour of private households in Germany showing a good fit in contrast to socio-economic variables. Bubeck et al. (2013) showed that coping appraisal is an important variable in terms of precautionary behaviour among flood-prone households along the river Rhine. In particular, response efficacy and self-efficacy contribute to the models of flood-adaptation behaviour. Similar results were found in other studies (Botzen et al. 2009, Terpstra et al. 2009, Botzen and van den Bergh 2012) confirming the importance of the coping appraisal for adaptation intentions. Zaalberg et al. (2009) carried out a comparative study between flood victims and non-victims in the Netherlands, showing that exposure positively affects protective motivation for future flooding. In addition to the PMT variables, a number of other factors may influence uptake. These include flood experience (Grothmann and Patt 2005, Kreibich et al. 2005, Siegrist and Gutscher 2006) as well as social networks such as neighbours or friends having implemented measures (Bubeck et al. 2013), or public provision of flood risk adaptation measures inducing moral hazard (Le Dang et al. 2014).

A number of studies conclude that communication for flooding and adaptation should focus on explaining the potential measures as well as on information on how to implement them (Bubeck et al. 2013, Maidl and Buchecker 2014, Clayton et al. 2015). While several studies have found that increased knowledge and information correlate positively with precautionary behaviour (Thieken et al. 2006, Miceli et al. 2008), numerous studies found no evidence of a direct effect of information sources and flood adaptation behaviour when risk perception was controlled for (Zaleskiewicz et al. 2002, Grothmann and Reusswig 2006, Botzen et al. 2009).

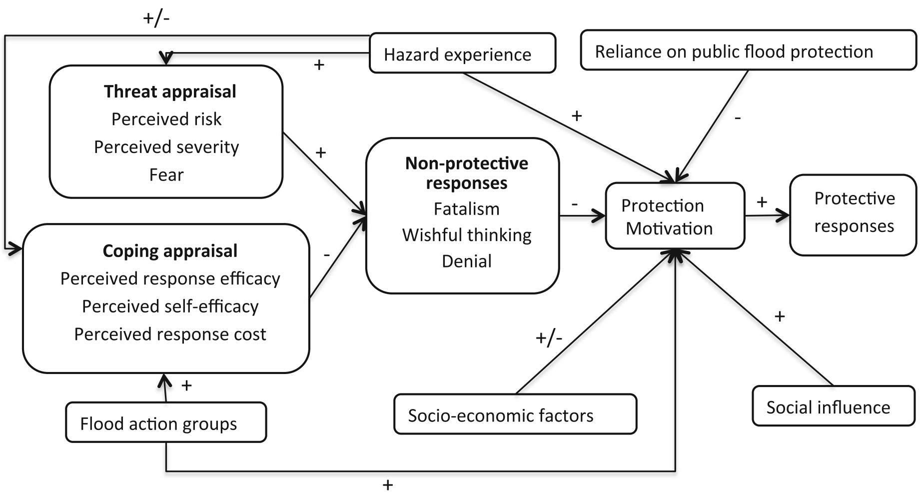
Behavioural decision research suggests that people may take action if they feel empowered to take charge rather than being treated as helpless citizens (Bush and Folger 1994, Page and Czuba 1999). Detailed, precise and personally relevant information might lead to more effective adaptation to flood risk (Klein 1998) such as proposing concrete easily implemented action which can alleviate the problem (Moser 2010).

Tentative evidence has been found for earthquake preparedness through targeted information campaigns (Lindell and Perry 2000). Further, communication research recognises that messenger choice is critical in the communications process (Moser 2010) and people are more likely to accept suggestions conveyed by people with similar views (Malka et al. 2009) such as peers as suggested by social learning theory (Bandura 1977).

We hypothesise that the activity of flood action groups works precisely through the mechanisms described above and can thus impact the motivation for implementing adaptation measures. The flood action groups provide information on a number of flood-related issues, including information and training on the use of flood adaptation measures, but also work as interest groups to lobby for flood protection schemes on the council level. They turn flooding into a locally relevant issue creating responsibility and ownership. In addition, flood action groups are locally grounded and people may thus be more likely to trust the recommended actions. Group members may influence neighbours and friends in the community who have been shown to be influential in PMT studies (Bubeck et al. 2013).

The hypothesised mechanisms within the PMT framework are presented in Fig. 1. The flood action groups may both affect the protection motivation directly but there may also be a mediating effect. The groups could positively impact self- and response-efficacy which in turn impact positively protection motivation.

The response variables within our analyses are household flood management measures. They include traditional measures, such as insurance and sandbags, but also more innovative and modern measures such as flood warnings and floodgates that have been specifically promoted or discussed by flood action groups.



(Adapted from Grothmann and Reusswig, 2005)

Fig. 1 Conceptual framework for the data analysis'

Flood insurance reduces the financial consequences of a flood once it occurs and is identified in other studies as an adaptation measure (Grothmann and Reusswig 2006, Bubeck et al. 2012b). Sandbags can slow down the penetration of water through buildings by acting as a barrier. Floodgates for households are installed in the case of flooding to hold back floodwater and generally provide very effective protection from flooding (SFF 2014). Flood warnings allow residents time to move valuable items to higher floors and to secure their properties with further measures.

In total 30 explanatory variables were gathered from the respondents based on the framework in Fig. 1, including their threat and coping appraisal, non-protective and protective responses, as well as socio-economic characteristics. Questions regarding financial aid by public authorities were included, which may provide a negative incentive to implement measures. Further, individuals may be influenced by neighbours and friends' adoption of measures (Ajzen 1991). Severity of experience of flooding in the near and distant past was also included as this has been observed to have positive effects on self-protective behaviour of natural hazards (Bubeck et al. 2012a). Finally, flood action group variables were included. Specifically, whether the respondents were aware of a flood action group in their community ('flood action group'), whether they were directly involved with the group ('involvement') as well as whether specific information was provided by the groups and whether the information was useful (see Table 1 for the different types of information and table A1 in the electronic supplementary material for a complete list of explanatory variables).

3 Materials and methods

Cross-sectional data from 124 private households across Scotland that have either experienced flooding or are at risk of flooding was gathered through a questionnaire-based survey and analysed with ordinal regression.

The questionnaire is based on the frameworks of Grothmann and Patt (2005) and Bubeck et al. (2013). It was refined with a pilot study of 18 flood risk households, and based on discussions with local flood groups and the Scottish Flood Forum (SFF) (an NGO that deals both with flood prevention and post-flood assistance). The results from the pilot study were used to further develop the questionnaire structure. The survey was distributed online and in paper format to 600 residents in 34 communities across Scotland where flooding has occurred in the past and thus flood action groups were formed since 2012. The survey was also distributed at a flood exhibition in Scotland to include respondents from communities without a flood action group and yielded a response rate of just over 20 %.

Table 1 shows a range of sample characteristics. All participants had experienced some flooding in the past and about 75 % classified their flood experience as very severe. 85 % of respondents have already implemented some form of flooding adaptation measure and 49 % of participants confirmed they were actively involved in the community flood action groups. In the communities surveyed, the flood action groups provide information on the flood risk strategy of the local council (44 %), flood warnings (66 %), information on private flood management measures (56 %) and, finally, information on how to use certain flood management measures (44 %). The sample characteristics are not perfectly representative of the Scottish population. For example, average age in the study are higher than in the overall population. The percentage of people over 65 is above the Scottish average (39 % in the sample versus 17 % in the Scottish population (National Statistics 2014). However, over-

Table 1 Sample characteristics (n = 124)

Variable	Percentage of total sample	Variable	Percentage of total sample
Age		Flood experience	
18–24	1	Yes	100
25–44	16	No	0
45–65	44		
65+	39	Flood adaptation measure	
		Yes	85
Gender		No	15
Female	51		
Male	49	Flood action group	
		Yes	84
Income		No	16
<£10,000	12		
£10,000–19,999	14	Involvement in flood action group	
£20,000–29,999	16	Yes	49
£30,000–39,999	10	No	51
£40,000–49,999	13		
£50,000–74,999	17	Information through group on	
£75,000–99,999	9	Flood risk strategy	44
> £100,000	9	Available measures	56
		Implementation of measures	44
Education		Flood warnings	66
Secondary education	29		
Diploma or vocational degree	22	Usefulness of the information	
Bachelor's degree	32	N/A	33
Master's degree	11	Not useful	6
Doctorate	6	2	8
		3	11
Ownership		4	16
Tenant	7	Very useful	27
Owner	93		

representation of some population subgroups does not appear to affect estimates of means and proportions and is unlikely to affect correlation and regression analyses (Huang et al. 2012, Terpstra and Lindell 2013).

3.1 Statistical model

The response variables were measured on a five-point Likert-scale and we thus estimate the effect of the potential determining factors on the different adaptation measures by using an ordered-logit model (Christensen 2015). We provide a polychloric correlation matrix in the electronic supplementary material (table A3) for all dependent and independent variables which shows that the correlation between predictor variables included in the models is moderate (around 0.4). As the dataset is small and about 11 % of the data per variable are missing due to non-responses, we used multiple imputation to compute the missing values stochastically in a way that accounts for uncertainty using the MICE package in R (Honaker et al. 2015) in order to improve the efficiency of estimation. We obtained five imputed datasets for our model selection. Despite the imputation, the observations to response variables ratio remains low, so backward selection is infeasible. For each of the response variables we therefore proceeded as follows: we entered each explanatory variable one at a time into an ordinal regression to determine which of the explanatory variables are significant at the 5 % level. We created the model that contains all of these variables, and then performed backwards selection on this model using the Wald-test eliminating the least significant variables at each step, until all of the variables that remain within the model are significant at the 5 % level.

The estimated regression coefficients are on the scale of the cumulative log odds; we present the exponential of these coefficients, which correspond to the cumulative odds, because these have a natural interpretation. For instance, we compare people who use flood warnings to an average extent (3 on the Likert scale) or less with people who use flood warnings more.

3.2 Analytic methods

We ran three regressions per measure: 1. implementation of the household flood adaptation measures prior to the foundation of the flood action groups as the response variable, 2. implementation after the foundation of the flood action groups, 3. motivation for future implementation of measures. The latter two regressions included variables testing for the influence of the flood action groups to compare communities with and without flood action groups. For communities where flood action groups are in place, we tested for the influence of specific information provided by the groups.

We also ran a mediation analysis based on the standard approach of Baron and Kenny (1986) to explore whether the flood action groups variables (X) may be correlated with either of the two components of the coping appraisal (Y) which in turn may be correlated with the uptake of the different measures (Z). To test for partial and complete mediation, we verify whether there are significant relationships in regression equations between X and Y (with Y being the outcome) and X and Z (with Z being the outcome). Then, we tested whether Y is related to Z while X is held constant. Additionally, we tested whether adding X in the regression equation of Z on Y statistically significantly improves the model by using Wald tests to show partial mediation. If we find no added significance, this suggests complete mediation, i.e. the mediator 'absorbs' the effect of the flood action variables. We also tested for mediation of flood experience through threat and coping appraisal as hypothesised in Fig. 1. We provide McKelvey Zavoina R^2 as goodness-of-fit measure.

The cross-sectional nature of data implies that the relationships should be interpreted as correlation rather than causation.

4 Results and discussion

Section 4.1 interprets the regression models for the four types of flood adaptation measures as well as the variables influencing response-efficacy and self-efficacy. Section 4.2 provides a short discussion.

4.1 Results

Table 2 presents the results of the regression equations. Across the four measures, more explanatory variables fitted to data from respondents were identified for the more recent uptake of flood risk management measures as well as for intentions in the near future. This makes sense for two reasons. First, people may not remember the exact extent of their use of, for instance, sandbags prior to 2012, and it may have varied over the time period. Second, the dataset is cross-sectional apart from the response variables. The respondents' perception may have changed over time but also their socio-economic status, so we find a better fit regarding their current opinions/status, which is reflected in current uptake and intentions for future uptake in the present.

4.1.1 Coping appraisal

Self-efficacy is significant within at least one of the analyses for each measure. Response efficacy is significant for the use of insurance (D3 and D5) and flood warnings (A5). This confirms findings of other studies (Grothmann and Patt 2005, Zaalberg et al. 2009, Bubeck et al. 2013) showing that the belief in the effectiveness of a measure and the level of confidence to implement the measure play a central role in the uptake of household flood management measures. The third variable of coping appraisal, response cost appears to be mostly non-significant. An exception is the cost for flood warnings with a negative coefficient for intended uptake (A5) indicating a lower use with higher cost. This is a surprising result for a low cost measure such as flood warnings. It might reflect the cost of accessing flood warnings, mostly provided through text messages or the internet, which could be more challenging for the predominantly older respondents of the survey. Receiving financial support is not significant in the regressions. The lack of significance of response cost and financial support highlight that cost is mostly not decisive when it comes to encouraging the uptake of less expensive adaptation measures confirming the findings of Terpstra and Lindell (2013) and Lindell et al. (2009). While it is surprising that cost does not have a negative effect on insurance, conversations with the flood action groups indicated that all households are keen to obtain flood insurance (if provided by the insurance company) despite the high cost.

4.1.2 Threat appraisal

Risk perception, a component of threat appraisal, is significant for a number of the analyses. Some studies have found a minor contribution of risk perception (Bubeck et al. 2013, Koerth et al. 2013) while others observe a strong link between increased risk perception and increased uptake of measures (Miceli et al. 2008, Bichard and Kazmierczak 2012, Osberghaus 2015). Due to the different formulation of risk it is challenging to compare the results across studies. We find significance for risk in particular for floodgates (C3-C5) and sandbags (B2-B5). This high and significant risk perception for these two measures may be related to the fact that they represent physical actions to avoid homes being flooded; where respondents' decisions to implement these emergency measures reveal their perception that the risk is real and high. The results indicate that high risk perception may lead to increased flood preparedness but appears to depend on the measure. We do not find significance for fear as the second component of threat appraisal.

Table 2 Results of the ordered logit models: variables associated with the pre-2012, post 2012 and intended uptake of flood warnings (A1-A5), sandbags (B1-B5), flood gates (C1-C5) and insurance (D1-D5), for all communities and for communities with a flood action group

	All communities				Communities with a flood action group			
		Log (odds ratio)	Odds ratio	McKelvey Zavoina R^2		Log (odds ratio)	Odds ratio	McKelvey Zavoina R^2
Flood warnings								
	A1							
	Pre-2012 uptake							
Threat appraisal								
Coping appraisal								
Flood action group variables								
Other variables								
	A2				A4			
	Post-2012 uptake			0.38	Post-2012 update			0.32
Threat appraisal								
Coping appraisal	Self-efficacy	0.65 (0.13)	1.9**		Self-efficacy	0.84 (0.16)	2.3**	
	Response cost	−0.35 (0.14)	0.7*					
Flood action group variables								
Other variables	Neighbours	0.28 (0.12)	1.3*					
	A3				A5			
	Intended uptake			0.37	Intended uptake			
Threat appraisal	Risk	0.46 (0.15)	1.6***					0.50
Coping appraisal	Self-efficacy	0.79(0.14)	2.2***		Self-efficacy	0.53 (0.19)	1.7*	
					Response-efficacy	0.58 (0.22)	1.8*	
Flood action group vaiables					Information on flood warnings	1.26 (0.54)	3.5*	
					Information on flood risk strategy	1.16 (0.44)	3.2*	
Other variables								
Sandbags								
	B1							
	Pre-2012 uptake							
Threat appraisal								
Coping appraisal								

Table 2 (continued)

	All communities				Communities with a flood action group			
		Log (odds ratio)	Odds ratio	McKelvey Zavoina R^2		Log (odds ratio)	Odds ratio	McKelvey Zavoina R^2
Flood action group vaiables								
Other variables								
	B2							
	Post-2012 uptake							
Threat appraisal	Risk	0.62 (0.15)	1.9***		Risk	0.71 (0.18)	2***	
Coping appraisal	Self-efficacy	0.62 (0.15)	1.5***		Self-efficacy	0.56 (0.16)	1.8***	
Flood action grooup variables								
Other variables								
Flood gates								
	C1							
	Pre-2012 uptake							
Threat appraisal								
Coping appraisal								
Flood action grooup variables								
Other variables								
	C2				C4			
	Pre-2012 uptake			0.13	Pre-2012 uptake			0.17
Threat appraisal					Risk	0.4 (0.18)	1.5*	
Coping appraisal	Self-efficacy	0.38 (0.13)	1.5**					
Flood action grooup variables					Information on implement	1.29 (0.41)	3.6**	
Other variables	Implementation with neighbours	0.78 (0.35)	2.2*					
	C3				C5			
	Intended uptake			0.33	Intended uptake			0.44
Threat appraisal	Risk	0.64 (0.16)	1.9***		Risk	0.73 (0.20)	2.1***	
Coping appraisal	Self-efficacy	0.60 (0.13)	1.8***		Self-efficacy	0.73 (0.17)	2.1***	
Flood action grooup variables					Neighbours	0.4 (0.15)	1.5***	
Other variables								

Table 2 (continued)

	All communities				Communities with a flood action group			
		Log (odds ratio)	Odds ratio	McKelvey Zavoina R^2		Log (odds ratio)	Odds ratio	McKelvey Zavoina R^2
	D1							
	Pre-2012 uptake			0.10				
Threat appraisal								
Coping appraisal	Self-efficacy	0.27 (0.12)	1.31*					
Flood action grooup variables								
Other variables	Neighbors	0.27 (0.12)	1.31*					
	D2				D4			
	Post-2012 uptake			0.12	Post-2012 uptake			0.19
Threat appraisal								
Coping appraisal								
Flood action grooup variables								
Other variables	Ownership	2.41 (0.71)	1.1**		Ownership	2.29 (0.85)	9.9**	
					Overall flood experience	−0.73 (0.35)	0.48*	
	D3				D5			
	Intended uptake			0.14	Intended uptake			0.15
Threat appraisal								
Coping appraisal	Response efficacy	0.32 (0.13)	1.4*		Response efficacy	0.36 (0.15)	1.4*	
Flood action grooup variables					Information on available measures	1.16 (0.44)	3.2*	
Other variables	Ownership	1.96 (0.64)	7.1**					

Signif. codes: 0.001 ‘***’ 0.01 ‘**’ 0.05 ‘*’

Standard errors in parenthesis

4.1.3 Social environment, previous flood experience, socio-economic variables, non-protective answers

We note the significance of neighbours in the use of insurance (D1), flood warnings (A2), floodgates (C2 and C4), as in other studies confirming the importance of the influence of peer behaviour (Bubeck et al. 2012a, Bubeck et al. 2013). For the use of floodgates post-2012 (C2), we find significance for the variable ‘implementation with neighbour’. This likely reflects that non- or semi-detached houses require joint measures such as floodgates to protect the homes. Therefore, a respondent who has implemented a measure together with their neighbour is more likely to have set up a more sizeable floodgate.

Flood experience has only been found to be significant for the post-2012 insurance regression (D4) with a negative coefficient. The negative coefficients of flood experience is counter-intuitive, but other studies have found similar results (Kreibich et al. 2011b, Bubeck et al. 2013) and have been linked to higher insurance premiums due to an increased of risk to flooding. The lack of significance of flood experience for other variables may be explained by a complete mediation of experience on uptake through threat and coping appraisal (Bubeck et al. 2013). Indeed, in our mediation analysis, we find mediation effects for flood experience variables for floodgates (analyses E1 and E1 in Table 3) through both threat and coping appraisal and for sandbags for the former (analysis F1). For a complete list of the mediation results see table A4 in the electronic supplementary material.

In line with other studies (Grothmann and Reusswig 2006, Zaalberg et al. 2009, Bubeck et al. 2013, Osberghaus 2015), socio-economic variables explain relatively little of the data. Here, we only find that ownership positively influences the uptake of insurance (D2-D5) which is not surprising given the owners financial responsibility. Finally, we found no significance for non-protective responses once controlling for other variables.

4.1.4 Flood action groups

We find a positive relationship where flood action group variables contribute significantly to the explanation of the data (A5, C4, C5, D5), indicating that such groups may positively influence the uptake of household flood management measures. We find significant links for variables which represent specific information provided by the flood action groups and uptake of measures.

We can speculate about the direction of the effect for insurance due to the cross-sectional data: the variable ‘having obtained information on available measures’ is significant for the intended uptake of insurance for communities with a flood group present. This may reflect that people who are at risk of flooding and have an expensive insurance premium, or even struggle to obtain insurance, are more likely to obtain further information through the flood action groups. This was confirmed by talking to the flood action groups. The members aim to find other solutions to flood risk beyond insurance and indeed we find significant correlations between insurance and the other measures of between 0.3 and 0.7. These findings have been confirmed by other studies (Hudson et al. 2015, Lindell and Hwang 2008, Lindell et al. 2009). However, there may also be an exchange in the groups regarding the most appropriate insurance cover, which was also confirmed by the groups themselves, which may result in a more comprehensive cover for members.

For floodgates, we find a positive effect of factor 3.6 for post-2012 uptake if respondents received information on how to implement specific measures. The flood action group members confirmed in personal conversation that the setting up of floodgates was discussed and demonstrated as part of the flood action group activities.

Table 3 Significant results of the mediation analysis for mediation of flood experience variables and flood action group variables through coping and threat appraisal. The figures provided in the table specify the *p*-values for the equations on top of the columns testing their significance

	Dataset and variables tested for mediation	Response variable Z	Mediator Y	Explanatory variable X	Z = bX	Z = aY + bX vs. Z = bX	Z = aY + bX vs. Z = aY	Y = bX
Flood gates								
E1 Partial mediation	Flood action group variables							
	Communities with flood action group	Intended uptake	Response efficacy	Usefulness	0.007	0.033	0.045	0.049
			Self-efficacy	Information on available measures	0.002	0.006	0.037	0.007
	Flood experience variables							
			Self-efficacy	Post-2012 flood experience	0.015	0.003	0.035	0.035
	All communities	Intended uptake	Threat	Post-2012 flood experience	0.015	0.038	0.035	0.000
			Threat	Average flood experience	0.009	0.025	0.040	0.000
E2 Complete mediation	Flood action group variables							
	Communities with a flood action group	Intended uptake	Self-efficacy	Information on implementation	0.020	0.002	0.177	0.001
			Response efficacy	Information on implementation	0.020	0.036	0.090	0.000
	Flood experience variables							
	All communities		Risk	Post-2012 flood experience	0.015	0.002	0.143	0.000
		Intended uptake	Risk	Average flood experience	0.009	0.001	0.171	0.000
			Response efficacy	Post-2012 flood experience	0.022	0.002	0.376	0.000
Sandbags								
F1 Complete mediation	Flood experience variables							
	All Communities	Post-2012 uptake	Risk	Post-2012 flood experience	0.040	0.002	0.520	0.000
			Risk	Average flood experience	0.022	0.002	0.376	0.00
Flood warnings								
G1 Complete mediation	Flood action group variables							
		Post-2012 uptake	Self efficacy	Usefulness	0.021	0.008	0.212	0.014
			Response efficacy	Usefulness	0.021	0.005	0.244	0.004
		Intended uptake	Self efficacy	Usefulness	0.009	0.001	0.199	0.014
			Response efficacy	Usefulness	0.009	0.000	0.173	0.004
	Communities with a flood action group	Post-2012 uptake	Self efficacy	Information on implementation	0.046	0.000	0.641	0.005

Table 3 (continued)

Dataset and variables tested for mediation	Response variable Z	Mediator Y	Explanatory variable X	Z = bX	Z = aY + bX vs. Z = bX	Z = aY + bX vs. Z = aY	Y = bX
	Intended uptake	Response efficacy	Information on implementation	0.046	0.000	0.191	0.028
		Self efficacy	Information on available measures	0.012	0.001	0.541	0.004
		Response efficacy	Information on available measures	0.012	0.000	0.117	0.031
	Post-2012 uptake	Self efficacy	Information on flood warnings	0.001	0.008	0.123	0.000
	Intended uptake	Self efficacy	Information on flood warnings	0.001	0.003	0.202	0.000
All communities	Post-2012 uptake	Self efficacy	Existing schemes	0.012	0.001	0.551	0.000
		Response efficacy	Existing schemes	0.012	0.001	0.228	0.000
	Intended uptake	Self efficacy	Existing schemes	0.022	0.000	0.325	0.000
		Response efficacy	Existing schemes	0.022	0.005	0.199	0.000

For flood warnings, we find an increased likelihood of intended uptake of factor 3.5 if information on flood warnings was provided by the flood action group. Similarly, if respondents have received information about the flood risk strategy of their council, they have a higher likelihood of using flood warnings in the future. We can speculate whether this is due to local authorities recommending the use of flood warnings or the insight of the respondents that structural flood risk schemes may take considerable time to materialise. We find no link for sandbags. This may reflect that sandbags are long-standing household flood adaptation measures and the flood action groups cannot increase uptake. Indeed, about 60 % of respondents already used sandbags in both samples before 2012.

We find significant mediating effects of self-efficacy and response efficacy with respect to floodgates and flood warnings (analyses E1 and G1 in Table 3). For the uptake in the nearby future of floodgates, both partial and complete mediation are present if the obtained information from the group is perceived as 'useful', when 'information on available measures' has been provided. The number of significant mediating relationships is more extensive for flood warnings and applies to both post-2012 and intended uptake of flood warnings. The same variables as for floodgates are significant but in addition also whether 'information on flood warnings' have been provided and 'information on how to implement measures'.

There is also complete mediating effect of, 'existing schemes' for the use of flood warnings for the whole sample for post-2012 and intended uptake. Existing schemes refer to assistance (including that from flood action groups but also from the local council) with household flood management measures. While we cannot pin down the exact mechanism of 'existing schemes' on response and self-efficacy, we can deduce that specific help and information for flood risk at the household level appear to have a positive effect.

4.2 Discussion

The fitted models indicated a positive effect on uptake for insurance, floodgates and for flood warnings for flood action variables. It appears that having a flood action group in the community, or being involved in one, does not necessarily lead to an increased uptake of measures as the variable 'flood action group' and 'involvement' did not prove significant. It is rather when the groups provide tailored information such as on flood warnings or how to implement measures that significant correlations were observed.

We also find partial and complete mediating effects through the correlation of the flood action groups variables with increased self-efficacy and response-efficacy which are in turn associated with uptake. We detect significant correlations for floodgates and flood warnings which were promoted among the groups, if specific information had been provided which is also subsumed in the significance of the variable whether the obtained information is perceived as 'useful'. Thus, tailored information appear to positively impact the confidence in implementing these measures as well as the belief in their effectiveness. These coping appraisal variables are key for protection motivation as observed in our regressions and in other studies using PMT as theoretical framework.

The UK government encourages autonomous adaptation to climate change, with flooding being one of the major expected climate change impacts in the UK (Defra 2013). If the flood action groups can be 'kickstarted' with the help and direction of the council and the SFF their subsequent running will be ensured by the community itself, relying on active and engaged community members. The support of groups in the study by their local councils was limited to providing sandbags. While we do not have estimates of the costs of running flood action groups, we know that household flood management measures often exhibit high benefit-cost ratios (Holub and Fuchs 2008, Kreibich et al. 2011a), and would therefore expect its cost to be below that of a structural measure for the same benefit. Indeed, flood protection on the household level and supported by the community may prove to be the only viable solution for many small communities where larger structural flood defence measures will not pass a cost-benefit test due to a too small population.

A number of caveats need to be considered. First, the sample ($n = 124$) is very small, which sets a limit to the complexity of the model and the robustness of the inference. This highlights the importance of conducting research on a larger scale to confirm the results of the study. Second, a more comprehensive measure of risk perception would have been feasible and delivered different results. This includes, amongst others, dread and unknown risk (Fischhoff et al. 1978), and combining these with well known disaster risks (Trumbo et al. 2016) or people's expectations of the personal impacts caused by a disaster (Huang et al. 2012, Mileti and Peek 2000, Mileti and Sorensen 1987). Third, the changes in uptake of certain measures may also partly be due to external reasons not captured in the study, such as easier access to flood warnings or the challenge of obtaining flood insurance for certain high risk properties.

5 Conclusion

This study examined the factors influencing the uptake of four household flood adaptation measures in small communities around Scotland using a cross-sectional survey ($n = 124$) within an extended framework of PMT. The main focus was on testing whether local flood action groups, in which residents promote the deployment of flood management measures, have a positive effect on uptake. The fitted models indicated a positive effect for the use of insurance and of floodgates, if information on measures and implementation were provided; for flood warnings we detected a link if specific information on flood warnings were provided. Additionally, we found a mediating effect for flood warnings and floodgates: some flood action group variables appear to positively impact the coping appraisal variables which are key for protection motivation. We conclude that flood action groups may increase the uptake of precautionary measures in particular by providing specific information. Given limited resources of local authorities, the promotion of well-designed flood action groups might provide a cost-effective way of increasing household resilience to flooding in Scotland and elsewhere.

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